Effects of Geotextiles on the Load-Carrying Capacity of Pavements on Sabkha

by

Zaki uddin Siddiqi

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

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DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

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In

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بسم اللّه الرّحمن الرّحيم

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
DHAHRAN, SAUDI ARABIA
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This Thesis, written by **Zaki Uddin Siddiqi** under the direction of his Thesis Advisor, and approved by his Thesis Committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of

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عمادة الدراسات العليا
DEANSHIP OF GRADUATE STUDIES

23/6/2000
Date:

This Humble work is Dedicated to:

My Parents, Sisters and Brothers

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All praise and gratitude be to Almighty Allah Subhanahu wa Ta'ala, the Most Gracious, the Most Merciful; the Almighty, whose blessings and help are all the time with me and He is the only one who helps and His help is the best of all. Peace and blessings of Allah be upon the messenger of Allah prophet Muhammad (peace be upon him).

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Abstract

Name: Zaki Uddin Siddiqi
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Sabkha soil is widely spread in the Arabian Peninsula, particularly along the Arabian Gulf and Red sea coasts. This soil is associated with some geotechnical problems due to its water sensitivity, low load-carrying capacity and chemical instability. Because of these inferior characteristics, roads constructed on sabkha terrains are subjected to deterioration in the form of raveling, cracking, rutting, formation of potholes and depressions.

The main objective of this research is to upgrade the load-carrying capacity of pavements constructed on sabkha soils using geotextiles, and to assess the effect of geotextile grade, base thickness, loading type (static and dynamic) and moisture condition (as-molded and soaked) on the performance of soil fabric aggregate (SFA) systems. In addition, the sabkha soil was treated with different percentages (5, 7, and 10%) of Portland cement and the performance of cement-stabilized sabkha was compared to that of SFA system under different testing conditions. All systems were evaluated by measuring load-carrying capacity at a given value of permanent deformation at the surface of the graded base layer under both as-molded and soaked conditions, taking into account the different testing parameters.

The results of this program indicated that the use of geotextile in the construction of roads on sabkha subgrades will have a beneficial effect on their load-carrying capacities, especially under wet conditions. The sabkha system with geotextile can carry much higher loads compared to the system without the geotextile, especially under soaked conditions. The improvement in the load-carrying capacity of sabkha samples with five percent Portland cement was lower than the ones with A-400 geotextile. However, samples with 7 and 10 percent cement additions showed better results than the inclusion of geotextile.

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ملخص الرسالة

الإسم: زكي الدين صديقي
العنوان: تأثير الانسجة الصناعية على مقدارتحمل الطرق المنشأة فوق التربة السبخية
التخصص: هندسة مدنية (نقل)
تاريخ الدرجة: يونيو - ٢٠٠٠م

تنتشر التربة السبخية في أنحاء مختلفة من الجزيرة العربية وخصوصاً على سواحل الخليج العربي والبحر الأحمر. وعادة ما يصاحب وجود التربة السبخية بعض المشاكل الجيوتقنية وذلك لحساسيتها للماء وقلة قوتها وعدم ثبات التربة السبخية كيميائياً. ولذلك، فإن الطرقات التي يتم إنشاؤها على التربة السبخية تتعرض إلى العديد من المشاكل مثل تطاير حصمة الأسفلت، ظهور الشقوق والتصدعات، والتخدد، وكذلك تكوّن الحفر والهبوطات.

يهدف هذا البحث إلى دراسة زيادة مقدرة تحمل الطرق المنشأة على التربة السبخية، وذلك بإستخدام الانسجة (الالياف) الصناعية، وكذلك دراسة تأثير أنواع الانسجة، وسمك طبقة الأساس، ونوع الاحمال (ثابت أم متردد)، وكذلك نسبة محتوى المياه (طبيعية أم مغمورة) على خواص التربة السبخية المدعمة بالأنسجة. وقد تم في هذا البحث أيضاً معالجة التربة السبخية بنسب مختلفة من الأسمنت البورتلاندي (٥، ٧، و١٠%) ، وتم بعد ذلك مقارنة خواص التربة المعالجة بالأسمنت بالتربة المحسنة بالأنسجة وذلك تحت ظروف إختبارية مختلفة. ومن ثم، تم مقارنة قوة مقاومة التربة المحسنة بالأنسجة مع التربة التي لم يتم تحسينها تحت ظروف إختبارية مختلفة.

وقد أوضحت نتائج هذا البحث أن إستخدام الانسجة الصناعية في إنشاء الطرق المقامة على تربة سبخية سيؤدي إلى زيادة القدرة التحملية للسبخة وبالتالي تحسين أداء وخواص الطرق المبنية على السبخات وخصوصاً عند إرتفاع نسبة المياه. وقد زاد مقدار التحسن بشكل أكبر في حالات البلل الكامل. وأظهرت نتائج هذه الدراسة أن القدرة التحميلية للتربة السبخية المدعمة بالنسيج الصناعي أكثر من قوة السبخة المعالجة بنسبة ٥% من الأسمنت.

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Chapter 1

INTRODUCTION

1.1 General

The rapid and extensive development in eastern Saudi Arabia has recently led to the construction of huge industrial cities, development of new residential areas and the associated network of roads. This resulted in the utilization of virgin lands for such large constructions and the large-scale urbanization programs. The Eastern Province of Saudi Arabia has somewhat unique geotechnical problems because the soils available for construction are, mostly, problematic and the loading and environmental conditions are extremely harsh. Many construction and post-construction problems have been reported in the literature when these soils are used without the realization of their abnormal behavior (Aiban et al., 1998a).

Roads constructed on sabkha terrains often suffer different classes of damage due to the low load-carrying capacity of sabkha deposits, especially when becoming wet (Aiban et al., 1998b). Sabkha is a saline, evaporative flats that form under arid climates and is associated with shallow ground water tables. The main characteristic of sabkha soils is that when it is dry, it possesses a sufficient bearing capacity and is hard enough to support traffic loads. However, when it is wet, it is impassable and it loses its supporting capacity. Hence, sabkha is considered very poor subgrade for road construction since it is wet most of the times.

The problems associated with sabkha soils are highly challenging and their consequences are not yet fully understood. Such a situation presents an unacceptable risk in normal practice and calls for the improvement of the geotechnical properties of such soils prior to any major engineering construction in such soils (Al-Amoudi, et al., 1995). Several techniques have been implemented to improve the inferior sabkha properties, with various degrees of success. These include soil replacement, vibratory compaction, and deep soil densification using vibroflotation, stone columns, and dynamic compaction (Abduljauwad et al., 1994).

The use of geotextile is one of the most promising and cost effective means of stabilizing poor soils world wide for many applications such as road and railroad construction, irrigation, drainage, erosion control, etc. (Koerner and Welsh, 1980). Some previous research and experimental work performed on sabkha soils indicated that the use of geotextile could be an efficient and cost effective solution for some construction problems in sabkha soils.

1.2 Geotextile Applications

Geotextiles have pervaded almost all the branches of geotechnical engineering and there is a large number of applications. Among these specific applications, geotextiles have been extensively used in the following areas of civil engineering: (Koerner, 1998).

- Road construction (paved and unpaved roads)

- Embankments
- Coastal protection work
- Land fills
- Hydraulic modifications
- Structural foundations

There is a large selection of geotextiles available commercially, manufactured from synthetic materials of different compositions to meet a wide range of applications. Any practical type of geotextiles should be composed of strong, durable, chemically inert materials that are highly resistant to the effects of ground conditions, weather and aging. In permanent installations, the long-term performance of the structure depends on the durability of the geotextile. As there are many applications for theses materials, geotextiles may have other specific requirements such as creep resistance or resistance to temperature or ultra-violet (UV) light exposure, etc. In summary, due to the very wide range of applications and the tremendous variety of available geotextiles having widely different properties. The selection of geotextile type, and the particular design method or design philosophy is a critical decision. This decision must be made before the actual mechanics of the design process are initiated (Koerner, 1998).

1.3 Use of Geotextile in Road Construction

One of the most common uses of geotextiles is in road construction and in soil stabilization, where soft and low-strength soil conditions prevail. In this application the geotextile is generally used in conjunction with the locally available aggregate such as crushed stone, shot rock, gravel, or sea shells to develop a structural support layer. For example, roads surfaced only with aggregate are continually being built to provide access to and around construction sites, logging operations, mining and quarrying operations, and as planned stage construction for higher type roads. Experience with these types of support systems has shown that geotextiles can be cost effective, and may allow substantial reductions in the quantity and possibly the quality of aggregates used (Robonett and Lai, 1980).

In the highway support systems, geotextiles are used to provide separation between subgrade soil and base or subbase layers and to stop the intermixing of these dissimilar materials. The fabric also provides reinforcement to the supporting system by giving tensile resistance and confinement to the granular materials. In addition, when large deformations occur, a geotextile will provide improved load support capabilities. It also acts as a filter media ensuring rapid consolidation of the subgrade. Fabrics are also being used as an interlayer between cracked and deteriorated pavement surfaces, and new asphalt concrete overlays in order to reduce the rate of reflective crack occurrence (Robonett and Lai, 1980).

1.4 Problem Definition

One of the typical problems in the construction of roads in the Eastern Province of Saudi Arabia and along the coastal regions of the Arabian Gulf and the Red Sea is the presence of the sabkha soils. Sabkha soils are associated with many geotechnical problems due to the presence of precipitated salts of different sizes, shapes and compositions; and by the shallow saline ground waters; thus it is considered a poor construction material. Because of these characteristics, some of the pavements located on sabkha flats are subjected to deterioration in the form of raveling, cracking, rutting and formation of potholes and depression in recently built highways and expressways (Farwana and Majidzadeh, 1988). The variability of the geotechnical properties of sabkha in both the horizontal and vertical directions, due to the presence of different digenetic minerals, could lead to excessive differential settlement (Akili & Torrance, 1981). Furthermore, their susceptibility to strength loss and collapse upon wetting makes their use in construction very risky and hazardous. In its natural state, sabkha soil is considered very poor, even if it is used as a subgrade layer for road construction. The purpose of this research is to upgrade the load-carrying capacity of sabkha soil as a subgrade, using geotextile and Portland cement and compare the two improvement techniques.

1.5 Research Objectives

The main objectives of this research is to assess the effect of geotextile types, base thicknesses, loading type and magnitude and moisture content (as-molded versus soaked) on the performance of Soil Fabric Aggregate (SFA) system when the base is resting on a sabkha subgrade. In addition, the sabkha will be treated with different percentages (5, 7, and 10%) of Portland cement and the performance will be compared to that of sabkha geotextile system under different conditions. The performance of the system will be measured by comparing the amount of load-carrying capacity of the system at a given value of permanent deformation of sabkha surface with and without geotextile and with and without cement treatment and under both as-molded and soaked conditions. If geotextiles are found to substantially improve the load-carrying capacity of sabkha, the results of this research will help in the optimization of the design of graded base layer for roads constructed over sabkhas.

1.6 Thesis Organization

In order to accomplish the above-stated objectives, a thorough survey of the published literature has been conducted to provide a basis for this research work. Literature review has been presented in Chapter Two. It mainly focuses on various aspects of the sabkha soils and the previous experimental results related to stabilization of sabkha soils using geotextiles. Chapter Three is devoted to the experimental program, presentation of the laboratory investigation program and discussion of the procedures and methodologies of the different testing and techniques carried out during the experimental work. Chapter Four, entitled results and discussion, outlines the results obtained from the laboratory testing and discusses these results thoroughly. Lastly, Chapter Five summarizes the main conclusions that can be derived from this research program. It also gives some recommendations for future work along this line.

Chapter 2

LITERATURE REVIEW

2.1 Sabkha Soil

2.1.1 General

The expression "sabkha" is originally an Arabic term that has long been in use to describe indefinitely saline flats that are underlain by sand, silt or clay, and often encrusted with salt (Al-Amoudi, 1995). This type of material has been distinguished as being prevalent in the Arabian Peninsula. They are of evaporatic formation, where the evaporated water is either from sea invasion or from the seepage of moisture from low-lying strata, further inland. In both of these cases, varying quantities of calcium carbonate, magnesium carbonate, calcium sulfate and calcium, magnesium and sodium chloride are found. The Military Engineering Experimental Establishment (1969) has produced a glossary of desert terms, which gives a more formal definition of the term sabkha as follows:

" Bottom of a closed depression, zone of evaporation for accumulated runoff from a shallow subterranean water-table, characterized by the presence of salt deposits and absence of vegetation. Usually consists of fine textured materials and is soft when wet. Can also be used for salt marshes or marine lagoons."

Sabkha soil is very heterogeneous and is mostly an unstable material. Its properties can vary in part with moisture content, fines content, salt type and quantities (Akili, 1981).

2.1.2 Sabkha Sediments

The sabkha sediments are predominantly sands with occasional layers of clay, clayey silts or silty clay. The fines content (silt and clay) in the sands is significant. The sand, in terms of mineral constituents, is mostly quartz, but carbonate and sulphate contents in sand size are also significant. Crystalline salts, often visible in the upper layer (one or two meters from surface), are comprised of gypsum, anhydrite, calcite and halite (Akili, 1981). In addition, calcareous sands and silts are prevalent in the sabkha sediments. Calcareous soils are usually those containing 12 to 50 percent carbonates as determined by solubility in HCl solution. For general characterization purposes, the sabkha sediments can be viewed as consisting of three zones (Akili, 1981):

Upper zone: extends from the crusty puffy surface down past the water table. This zone is approximately within two meters in depth and includes the cemented crust, the water table, and other thin stratified layers of cemented sands and silts above the water table. The material in this zone is generally medium dense to dense unless the surface has been inundated with rainwater or high tide water that may wash away readily soluble salts responsible for cementation of particles; such action creates a material with low density "loose" material.

Intermediate zone: may contain some or all of the following: loose quartz sands, calcareous sands, clay layers, mud and other marine derived sediments. This zone varies from very loose to medium dense, it can vary in depth from approximately two to ten meters, and it starts from the water table down.

Lower zone: In this zone, sediments generally exhibit high resistance to penetration. The likely materials encountered were dense to very dense sands, strongly cemented sands, stiff clays or rock. Based on SPT results, refusal may be encountered within a short depth of penetration.

One of the important features of sabkha deposits is the cementation process. In general terms, sabkha sediments consist of alternatively cemented and uncemented layers of sand and silts of varying thickness and properties. The evaporation from the sabkha surface causes interstitial pore fluid concentration and eventual formations of new evaporate minerals above and below the water table. These minerals are the major source of cementation that appear to bold sand and silt particles together to form cemented layers and cemented zones particularly in the near surface portion of the sabkha (Akili, 1981). There are various types of cementing agents such as pure silica, hydrous silicate, dolomite and halite and variety of carbonates. Calcium carbonate and more recent digenetic minerals such as gypsum are among the most widespread cementing agents.

Under normal dry conditions, the cemented sabkha surface provides an excellent running surface for wheeled vehicles and a hard base for road construction. Upon wetting or high water table conditions, the surface crust breaks and the sabkha site becomes impassible.

2.1.3 Distribution of Sabkha Soils in Saudi Arabia

Saudi Arabia has a large number of sabkhas, both continental and coastal. Akili (1983) reported that in the eastern region of Saudi Arabia, sabkhas occupy roughly about 25 %

of the coastal strip. Which is 50 km in width and 600 km in length, and extends from Kuwait in the north to the Qatar peninsula in the south. Sabkha also exists in the western, northern and southwestern regions of Saudi Arabia, as shown in Figure 2.1. In the western region of Saudi Arabia, coastal sabkhas exits at Obhor, Al-Lith and Yanbu, while in the southwestern region, sabkha exits near the town of Jizan. Continental sabkhas exist in the Wadi As-Sarhan in northern Saudi Arabia (Al-Amoudi et al., 1992).

2.1.4 Types of Sabkha Soils

Sabkhas are characterized as being large, flat, salt-encrusted, evaporative terrains situated along the coasts (coastal sabkha) or farther inland (continental or inland sabkha) of many tropical countries (Al-Amoudi and Asi, 1991). These soils usually form in hot, arid climates and are associated with shallow ground water tables that are within one and a half meters from the ground surface (Renfro, 1974). These two types of the sabkha soils are discussed in the following sections.

2.1.5 Coastal Sabkhas

These sabkha soils are thought to be the result of depositional off lap, at least in their seaward parts. Most of coastal sabkha soils are supratidal surfaces, which were developed as a result of a sedimentation sequence that appears to have started thousands of years ago with seawater transgressing over sand dunes. A general schematic diagram showing the possible sabkha process in coastal zones is shown in Figure 2.2. They are bordered by a semi-restricted lagoon on the seaward side and by a desert on the landward side. A coastal sabkha is usually stark, salt-encrusted, and essentially flat. Its surface dips very gently seaward at imperceptible rates, and does not normally exceed a few centimeters to

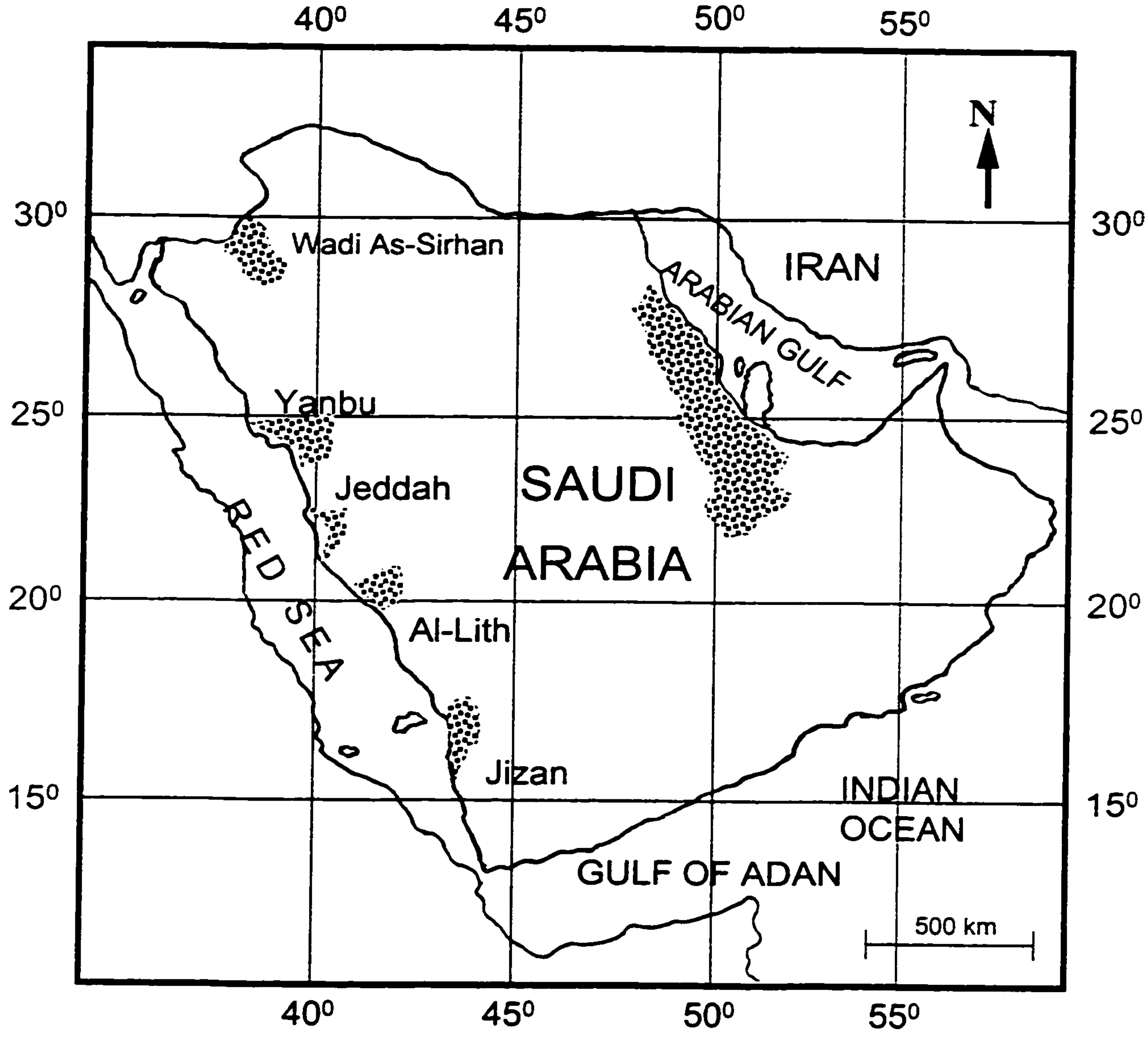


Figure 2.1: Distribution of sabkha soil in Saudi Arabia
(Redrawn from Al-Amoudi et. al., 1992)

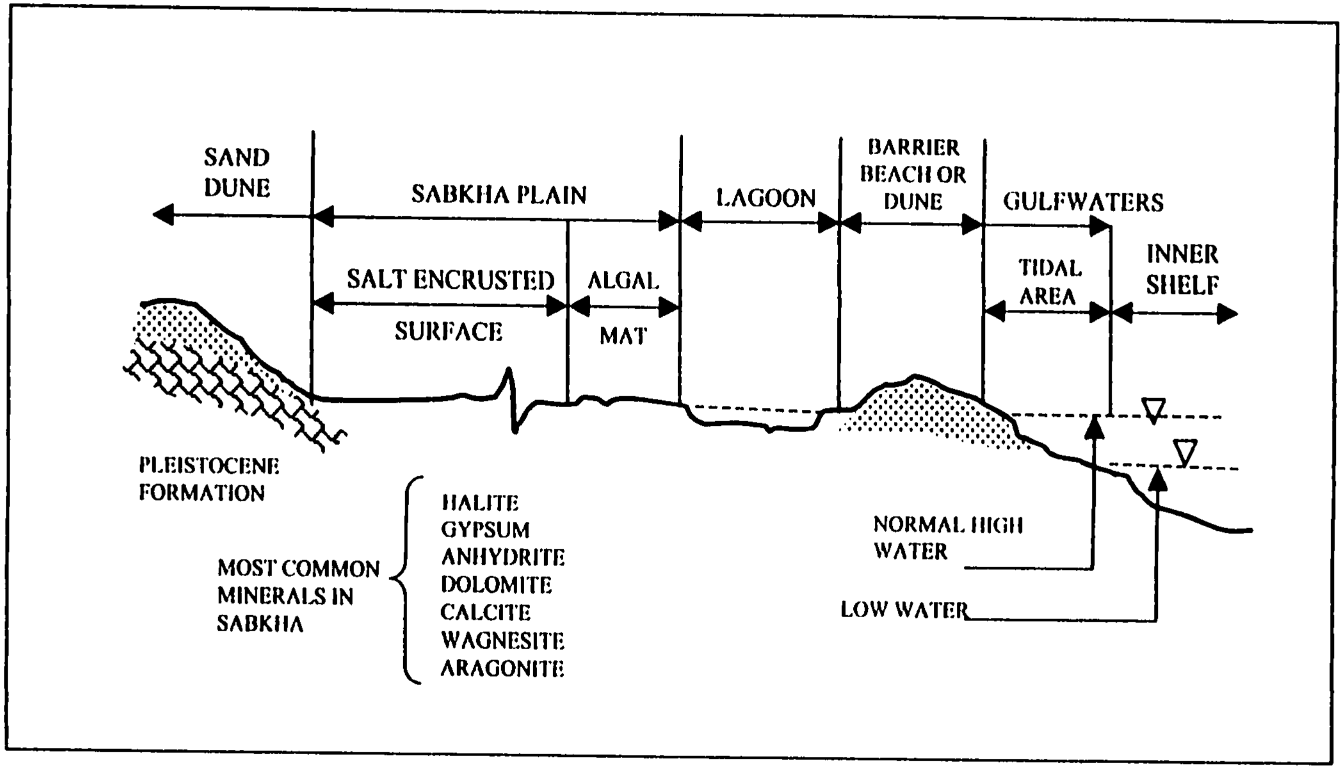


Figure 2.2: Generalized cross section across a coastal sabkha with typical surface features (Redrawn from Akili, 1981)

one or two meters in elevation above the mean high-water level (kinsman, 1969). An active sabkha is characterized by brine-saturated, porous and permeable sediments that are capable of supplying sufficient volumes of water to keep pace with, but not to exceed, water volume lost to atmosphere by evaporation (Renfro, 1974).

2.1.6 Continental or Inland Sabkhas

They usually develop as surfaces, from which the wind has removed the dry sediment particles, parallel to the water table, at levels that are controlled by the dampness of the sediments (Johnson et al., 1978). The rate of evaporation in inland sabkhas is supposedly higher than that in the coastal ones due to the more arid conditions. Evaporation through the surface causes both the formation of brines and the precipitation of evaporite minerals. This means that the groundwater table plays a far more influential role in the development of these sabkhas (El-Naggar, 1988). These sabkhas are usually less developed and older in age as compared with coastal ones. Inland sabkha soils are dominated by fine-grained soil ranging in size from 0.15 mm to very fine clay particles (Stipho, 1989). The sediments of these sabkhas are dominantly composed of gypsum (desert roses), quartz and calcite, with halite always existing at the crust.

2.1.7 General Characteristics of Sabkha

Following is a list of general characteristics of sabkha, which were described by different researchers:

- Sabkhas are characterized by (i) the presence of precipitated salt of different sizes, shapes and composition; (ii) the highly saline and shallow ground water table; and

(iii) the relatively hard crusty surface caused by salt encrustation and desiccation, (Ghazali et al., 1985).

- Sabkha is generally made of quartz sands and silts, which sometimes have small proportions of mud and clay. In addition, sabkha soils contain calcium sulphate and calcium carbonate. These carbonates work mainly as cementing agents of sabkha, (Akili, 1981).
- Some sabkha soils have gravel mixtures within their composition. The presence of these gravelly sediments is more common in the continental sabkha rather than the coastal sabkha, (Ghazali et al., 1985).
- Sabkha soil is generally described as an unconsolidated, heterogeneous, layered or unlayered sedimentological framework, bathed in highly concentrated, subsurface brines, (Akili et al., 1978).
- The natural moisture content of the sabkha soil deposits ranges from 8 to 65%, so this large variation in the water content leads to large changes in density, consistency and strength, (Iqbal et al., 1981).
- Sabkha soils are very sensitive to moisture whereby complete collapse and large reduction in the bearing capacity are anticipated when these soils get into contact with water. Such behavior is attributed to the fact that some of the cementing materials that bond the mineral grains of sabkha together are highly soluble in water such as halite, and less soluble materials such as gypsum, aragonite or calcite. These attributes make the sabkha soils susceptible to collapse upon wetting (Al-Amoudi et al., 1992).

2.1.8 Construction Problems Associated with Sabkha Soil

Sabkha soils are generally considered as unconsolidated, heterogeneous, layered or unlayered sedimentological framework, bathed in highly concentrated, subsurface brines (El-Naggar, 1988). Geotechnically sabkha soils are considered highly variable in terms of grain size and shape, texture, degree of cementation, digenetic minerals, layering, density, etc. The variability of its geotechnical characteristics and the presence of highly concentrated brines in its matrix are the distinguishing features of sabkha systems (Al-Amoudi et al., 1991).

Because of these characteristics, some of the pavements located on sabkha flats are associated with many engineering problems such as: raveling, cracking, rutting and formation of potholes in the recently built highways and expressways (Farwana and Majidzadeh 1988). Some of the construction problems due to the geotechnical characteristic of sabkha soil are summarized as follows (Al-Amoudi, 1995a):

- A decrease in strength of the surface crust of sabkha occurs as a result of rainfall, flash floods, storm tides, or merely due to absorption of water from the generally humid environments prevailing in the sabkha terrains.
- A potential variation in the compressibility characteristics of sabkha sediments, particularly in the uncemented layers, could lead to excessive differential settlement.
- The concomitant prevalence of both chloride and sulfate salts prevalent in sabkha sediments and its brines are highly corrosive to both concrete and steel. The effects of these salts enhance the susceptibility of reinforced concrete to deterioration caused by both sulfate attack and reinforcement corrosion.

- The inaccessibility of a large number of sabkha sites for part of the year, as they become impassable upon wetting, due to weakening or loss of the crust strength has sometimes hampered the construction activities.
- Swelling and shrinkage, which may cause large cracks or damage to buildings. This is caused by the changes in moisture content, (Iqbal et al., 1981).
- The crystallization of salts and formation of blisters, which result from the movement of soluble salts due to the capillary action, which is attributed to seasonal temperatures variations. These salts and blisters cause expansion and initiate surface cracks in pavements, (Tomilson, 1978).
- The potential adverse reaction and chemical changes that may influence sediment properties and structures embedded in them. For example, gypsum undergoes alternate hydration and dehydration under the hot and humid conditions that associate volume changes, (Akili et al, 1981).

2.1.9 Sabkha Soil for Road Construction

Sabkha soils often exist over relatively extensive areas, these soils display variable properties and heterogeneous nature thereby requiring different treatment for different types of constructions specially the foundation and road construction. Russel (1974) mentioned that in the Arabian Peninsula, the sabkha is used for road construction, because of the lack of better road-building materials in the area. In addition, Akili et al (1981) reported that many parts within the sabkha's terrains have been designated as potential construction sites because of their proximity to industrial areas or population centers, such as the industrial complexes in Jubail, Ras Tanura, Yanbu, Rabigh and Jeddah (Al-Amoudi, 1995).

It should be emphasized that sabkha is a very variable material and in the present state of knowledge the selection of sabkha for road works should normally be based on field trials. Attempts to use standard laboratory tests to predict field behavior have generally been unsuccessful. However, with more experience gained from field trials, it may be possible to select sabkhas on the bases of their chemical and physical properties, as determined in the laboratory. Therefore, field trials remain the most reliable methods of assessing the performance of sabkha as road-building materials. Road surface should be at least one meter above the highest water table that can exist during the life of the road (Al-Amoudi et al. 1983). The presence of water may create hazards such as:

(a) Swelling due to the transition of anhydrite to gypsum.

(b) Sulfate attack on cement stabilized material due to the high gypsum content.

(c) Retardation and possible prevention of the hardening process of the cement stabilization due to high gypsum content.

(d) Solution of halite crystals.

Acid formation is not considered a hazard when carbonates are available for neutralization. It is suggested that the main problem in using sabkha for road construction may be the crystallization of soluble salt and the hydration causing blisters, lifting, and cracking of bituminous surfaces over unstabilized bases. From these comments, it may be concluded that the people in the Gulf Area and South Africa would consider most sabkhas as unsuitable for use as a base under bituminous surfacing but acceptable for unsurfaced roads (Al-Amoudi, 1992).

2.1.10 Sabkha as Unsurfaced Road

The good performance of unsurfaced sabkha roads would appear to depend on the formation of a thin salt crust, which becomes very tightly compacted under traffic. In a humid area, the affinity for water of the salt in the sabkha enables it to hold enough water to bind the surfacing. However, at dawn and dusk when the humidity is at its highest the surface may become very slippery.

Rise in ground water table levels results in the excessive settlement due to the wetting and the compressibility of dewatered and loose soil. If the water table is not too shallow (at least 2.0 meter below the unsurfaced road), then deterioration of unsurfaced sabkha roads takes the form of potholing rather than rutting. Unsurfaced sabkhas may still play an important role for lightly trafficked routes, and the construction of properly engineered unsurfaced sabkha roads can be used as the first stage of a stage construction process in an arid environment (Al-Amoudi, 1992).

2.2 Geotextiles

Geotextile is a generic name given to fabrics that are placed in contact with soil as a reinforcing member or as a filter. They are defined by (ASTM D 4439), as a permeable geosynthetic comprised solely of textiles. Geotextiles are used with foundation, soil, rock, earth, or any other geotechnical engineering-related material as an integral part of a human-made project, structure, or system (Koerner, 1998). Geotextile is a name, which is universally adopted for the fabrics used in geotechnical engineering. Geotextiles are also known by various names such as construction fabrics, synthetic fabrics, filter fabrics, road rugs, or simply fabrics (Koerner and Welsh, 1980).

2.2.1 Types of Geotextiles

All types of geotextiles are made up of four main polymer families used as raw materials for geotextiles; polyester, polyamide, polypropylene, and polyethylene. The basic manufacturing choices for the geotextiles fabrics, which will ultimately have a tremendous impact on their physical properties are (Koerner, 1998):

i) The Woven Type

It is made from continuous monofilament fibers or continuous silt-film fibers. The polymer filaments are woven as in a normal tissue with filaments running in an orderly pattern, perpendicular to each other. The woven geotextiles are made on conventional textile-weaving machinery into a wide variety of fabric weaves. There are various methods for weaving like plain weaving, basket weave, twill weave and stain weave. These different methods of weaving technology have a direct influence on the physical, mechanical, and hydraulic properties of the geotextile.

ii) The Non-Woven Type

It is made from continuous filament or stable fiber (a short fiber). The fibers are bounded randomly by mechanical interlocking (needle punching), chemical bonding, heated calendar (thermal bonding) or other processes or combinations (Koerner, 1998). Thermally bonded non-woven geotextile are produced by spraying polymer filament on a moving belt passing through heated roller, leading to thermal bonding at filament cross-over points. There is no warp or wept direction in such type of geotextiles. Chemically bonded geotextiles are also formed by spraying polymer filament onto a moving belt in a random manner, but the next stage involves dipping or spraying the sheet of filament with a chemical binder called acrylic resin. The mechanically bounded geotextiles are formed by deliberately entangling the filaments to form comparatively loose bonds. These geotextiles are referred as needle punched geotextiles.

2.2.2 Functions of Geotextiles

A geotextile function is a specialized action of the geotextile, which is required to achieve a design purpose and results from a unique combination of geotextiles properties. The first step of design is certainly to identify the functions required by the geotextile in the intended application. Relationships between properties, functions and purposes are given in Table 2.1(Giroud, 1986).

There are at least 100 specific applications of geotextiles. In a given application, a geotextile can perform one of several functions. Many functions have been identified and the most important ones (Figure 2.3) are briefly presented below (Koerner, 1998):

i) Separation

Geotextile separation function can be defined as the placement of a flexible porous textile between dissimilar materials so that the integrity and functioning of both materials can remain intact or be improved. When used as a separator, the geotextile prevents coarse grains from being pressed out of the base or subbase coarse into the weak or soft subgrade. It also prevents the intrusion of fines, from the subgrade, into the base layer under the influence of traffic loads. For separation, geotextile can be placed between subgrade and stone base in paved and unpaved roads and airfields; between foundation and embankment soils for road way fills; between old and new

Table 2.1: Relationships* between properties and functions of geotextiles** and their purpose and location (Giroud, 1986).

Properties***	Functions	Purposes	Location
Thickness			
	Drainage	Remove excess water	Inclusion
Permeability			
	Filtration	Prevents piping	Interface
	Separation	Prevents mixing	Interface
continuity			
	Protection	Prevents damage	Interface
	Tensioned Membrane****	Provides reinforcement	Interface
Tensile Strength			
	Tensile Member****	Provides reinforcement	Inclusion
Friction			

* Only the principal relationships are shown (e.g., the thickness also has some influence on the filtration and the protection functions).

** This table is not only applicable to geotextiles, but to all geosynthetics except geomembranes.

*** The three key properties are underlined.

**** Tension Membrane and Tensile Membrane are the two reinforcement functions.

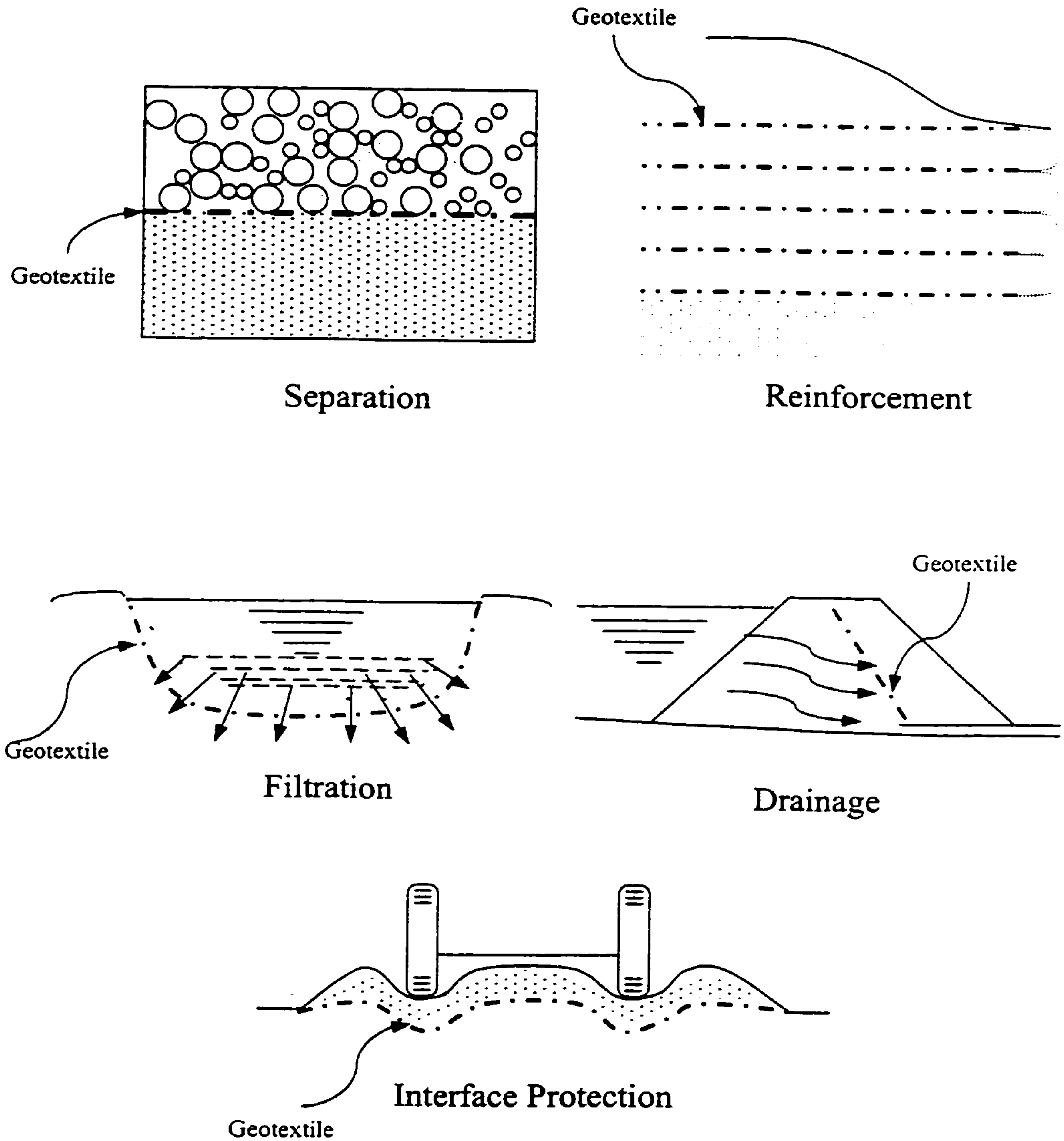


Figure 2.3: Basic functions of geotextiles

asphalt layers; between backfills and stone base courses. It can also be placed beneath parking lots, curb areas and sidewalk slabs.

ii) Reinforcement

Geotextile, as a material possessing tensile strength, can nicely complement materials that are good in compression but weak in tension. Thus low strength fine-grained silt and clay are prime candidates for geotextiles reinforcement. Problems involving subgrade reinforcement appear to be particularly well suited for fabric utilization. As reinforcing layers geotextile are placed over soft soils for unpaved roads, airfields, railroads, landfills, and non-homogeneous soils. Furthermore, they are used to reinforce jointed flexible pavements and between the base coarse and the subgrade soil to increase the load-carrying capacity of the soil.

iii) Filtration

A geotextile acts as a filter when it allows liquid to pass normal to its own plane, while preventing most soil particles from being carried away by the liquid flow. Two cases can be considered: (i) A geotextile, placed across a flow of liquid carrying fine particles, stops most of the particles (which therefore accumulate on the filter) while allowing water to pass through; (ii) A geotextile, placed in contact with a soil, allows water seeping from the soil to pass through, while preventing any migration of soil particles (with the exception of a very small amount of the finest particles located near the filter). Examples are the geotextiles used beneath the stone base for paved and unpaved roads and airfields, beneath ballast under railroads and between backfill soil and gabions (Giroud, 1986).

iv) Drainage

A geotextile provide fluid transmission (drainage) when it collects a liquid and conveys it, within its own plane, towards an outlet. All geotextiles provide such functions, but to widely varying degrees. Thin woven geotextiles can transmit liquid to an extremely low degree. Conversely, thick, nonwoven needle-punched geotextiles have considerable void space in their structure, and this space is available for liquid transmission. Examples are the use of geotextile as a drain beneath railroad ballast, behind retaining walls, in earth dams and beneath surcharge fill (Giroud, 1986).

v) Protection

A geotextile protects the material when it alleviates or distributes stresses and strains transmitted to the protected material. Two cases can be considered (Giroud, 1986):

- Surface Protection: A geotextile, placed on the soil, prevents its surface from being damaged by such actions as weather, light traffic, etc, and in some cases to provide a flat and clean surface for traffic. Use of geotextile in erosion control and helicopter pad is the examples of surface protection (Giroud, 1980).
- Interface Protection: A geotextile, placed between two materials, prevents one of the materials from being damaged by concentrated stresses applied by (or strains imposed by) the other material. Use of geotextiles in overlay design to alleviate the reflective cracking and in unpaved road to prevent heave of the soft subgrade soil between the wheels is the examples of interface protection (Giroud, 1980).

2.2.3 Relationships Between Applications and Functions of Geotextiles

It would be simple for both researchers and designers if only one function was performed in each type of application. In reality, a geotextile often performs several functions as presented in Table 2.2. From a practical viewpoint, it is interesting to group the application types in six areas: drainage, erosion control, containers, geomembrane support, soil reinforcement, and roadways (includes all types of traffic supporting structures). In Table 2.2, the dominant functions appear to be:

- Hydraulic Applications (drainage and erosion control): the fluid transmission and filtration functions.
- Geosynthetic Construction (containers, and geomembrane support): the tension membrane and protection functions.
- Geotechnical Structures (roadways and reinforcement): the tensile membrane and separation function, and, to a lesser extent, the tensioned membrane and protection functions.

2.2.4 Geotextile-Reinforced Unpaved Road

The first use of geotextiles in reinforcing roads was attempted by the South California Highway Department in 1926. A heavy cotton fabric was placed on a primed earth base, hot asphalt was applied to the fabric, and a thin layer of sand was placed on the asphalt. The Department published the results of eight field experiments in 1935: Until the fabric deteriorated, the roads were in good condition and the fabric reduced cracking, raveling, and localized road failure (Koerner and Welsh, 1980).

Geotextiles have been used extensively in the construction of unpaved roads. For a given thickness of aggregate layer, the traffic can be increased or, alternatively, for the

Table 2.2: Relationship between applications and functions of geotextiles (Giroud, 1986)

Application Category	Application Area	Application Type	Functions: Fluid Transmission	Filtration	Protection	Separation	Tensile Membrane	Tensile Member
Hydraulic Application	Drainage	Geosynthetic drains with filters (Geocomposites)	x					
		Geosynthetics drains without filters	x	x				
		Gravel drains, Pipes		x				
	Erosion Control	Silt fence, Silt curtains		x			x	
		Bank revetment		x				
		Erosion mat			x			
Geosynthetic Construction	Containers	Concrete foaming, Sand bags (hydraulic fill)		x			x	
		Gabions, Sand bags					x	
	Geomembrane Support	Bridging					x	
		Cushion			x			
Geotechnical Structures	Roadways*	Unpaved road (large deflection)				x	x	
		Asphalt overlays			x	x		
		Base Course (small deflection), Ballast						x
	Soil Reinforcement	Reinforced walls, Slopes and embakements						x

* Here roadways are considered to include all types of traffic supporting structures such as roads, parking lots, staging areas, railroad tracks, etc.

same traffic, the thickness of aggregate layer can be reduced, in comparison with the required thickness when no geotextile is used (Giroud, 1981). When the geotextile is placed between the subgrade and the stone or rock aggregate surface, two vital functions are served by this system: (Koerner and Welsh, 1980).

1) The fabric acts as a separator between the soil and the stone thereby preventing an intermixing of the two materials. This prevents contamination of the stone by the underlying soil, thereby maintaining its required high permeability and transmissibility characteristics.
2) When the soil subgrades are poor, that is, consisting of soft, compressible soils, the fabric plays a major role in the reinforcement process. In preliminary laboratory tests, it was found that the fabric placed on a soil would, acting alone, add as much as 4 CBR percent to the soil. In fact, the more the geotextiles are deformed as happens when they are placed over extremely soft subsoils, the greater the loads they can carry and therefore the less stone is required as a supporting layer above the weak soil.

2.2.5 Mode of Action

The placement of geotextile at the subgrade level, as shown in Figure 2.4, serves two major functions separation and reinforcement. In separation function it prevents the penetration of subgrade soil into the subbase and controls the movement of aggregate into the subgrade under traffic loads. As a reinforcement layer, the geotextiles can be used in permanent roadway system at the base (or subbase) and subgrade interfaces, were it serves to distribute the load, to reduce localized stresses and to increase load-carrying

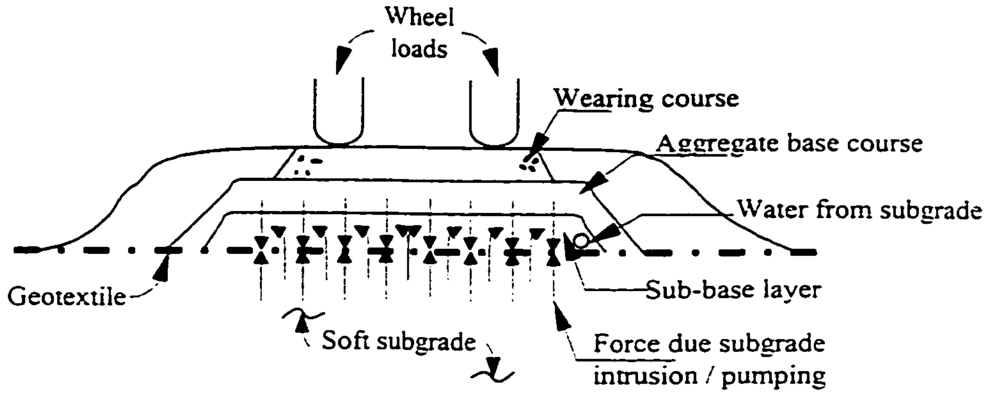


Figure 2.4: Concept of geotextile as a separator (Rao and Raja, 1990)

capacity of the system. Geotextile can serve as reinforcement in the following manners (Rao and Raja, 1990):

i) Base and subgrade restraint

Under loading, the pavement behaves like a beam in bending. Therefore, the top layer of base course experiences compression and the bottom layer experience tension. The aggregates of the base, with no tensile resistance, tend to move apart allowing intrusion of the soft subgrade. A geotextile placed at interface will restrain the aggregate movement. Moreover, friction developed along the interface between aggregate-geotextile and friction/adhesion at the geotextile-soil interface create a composite material of aggregate and soil with favorable qualities of ductility and tensile strength.

ii) Lateral restraint reinforcement

Concentrated stresses due to imposed vehicular loading can cause a punching or local bearing capacity failure at the points of contact between the aggregate and subgrade. If a geotextile is placed at such a depth where it intersects the failure surface of the bearing strata, as shown in Figure 2.5, it modifies the failure surface. Such an effect increases the bearing capacity or resistance to shear flow of the soil.

iii) Membrane type support of wheel loads

Excessive wheel loads can cause plastic deformation of the soft subgrade. A geotextile placed between the base and subgrade will act as a membrane support. As the roadway undergoes large deformations, the fabric is stretched and develop in-plane stress perpendicular to the plane of fabric to provide support to vehicular loading as shown in Figure 2.6.

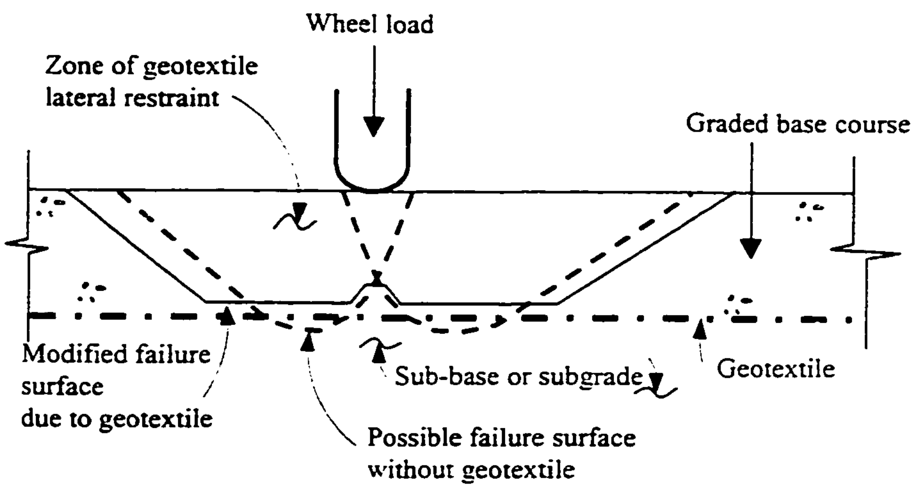


Figure 2.5: Concept of lateral restraint due to geotextile (Rao and Raja, 1990)

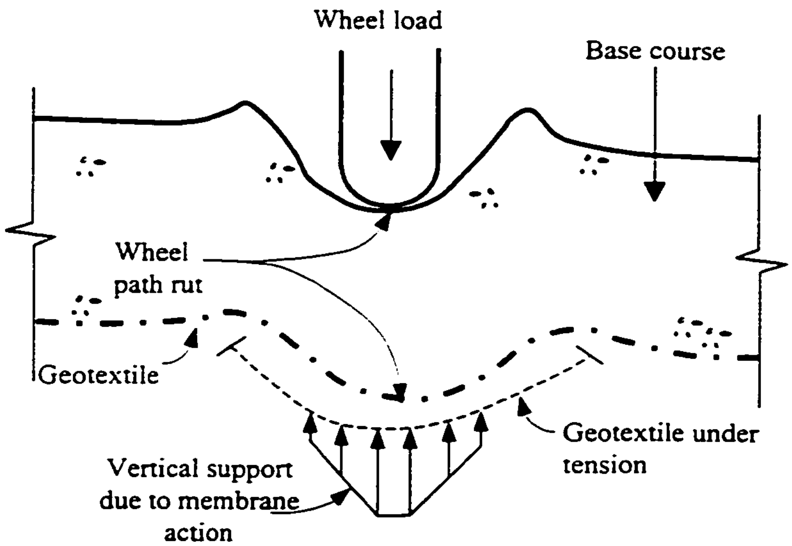


Figure 2.6: Concept of membrane type of support after rutting due to geotextile (Rao and Raja, 1990)

2.3 Previous Work on Soil-Fabric-Aggregate (SFA) Systems

There have been many researches and studies undertaken to define the mechanism of SFA by studying the effect and behavior of geotextiles when they are placed between the subgrade and the subbase in road construction. Most of the published information indicates that the fabrics do improve the static and dynamic loading characteristics of the SFA system when high deformations are experienced with soft subgrades. In this section, an attempt is made to review some of the known work, which has been conducted to study the behavior of soil-fabric-aggregate (SFA) systems. Model tests, full-scale field tests and theoretical developments have been performed to study the behavior of SFA system. Some of these studies will be described in the following subsections.

2.3.1 Theoretical Development

Several models have been developed to evaluate and calculate the structural benefit that can be gained from the fabric in a SFA system. Most of the models lead to the conclusion that the structural benefit gained from the fabric is function of fabric stiffness and magnitude of rutting.

Barenberg (1980) performed many studies in using fabrics in Soil Fabric Aggregate (SFA) systems since 1975. He reported that for the same loading conditions; systems with fabrics could be constructed with a significantly thinner aggregate layer and still provides the same level of performance. In one of his studies undertaken in 1975, he evaluated the effect of fabric properties on the behavior and performance of SFA systems. This was primarily a theoretical study using sophisticated mathematical models to simulate the results of SFA systems under load. From the results of the study, it was found that the properties of the geotextiles (specially the modulus) in the system could have a very significant effect on the behavior and performance of SFA system.

Giroud and Noiray (1981) have developed a method to calculate the required thickness of aggregate layer and make the proper selection of the geotextile to be used. They began their procedure using geometrical relationships to describe identical situations with and without the use of geotextile reinforcement. They introduced the hypothesis that soil resistance increased from π to $(\pi + 2)$ times the undrained shear strength when the geotextiles are used. They developed well-known equations, which were plotted to result in a family of curves showing the aggregate thickness required when no geotextile is used and the savings in aggregate thickness when various geotextiles are used. Typical set of their findings is shown in Figure 2.7.

Sellmeijer et al., (1982) have developed a calculation method by which the increase in bearing capacity of the road due to the geotextile reinforcement can be determined. Their method fulfills the equilibrium conditions of the geotextile and the subgrade simultaneously. The calculation method was programmed in a pocket calculator. This enables determination of the aggregate height and the required geotextile strength as a function of the properties of aggregate and subgrade, traffic condition, and rutting. They developed two types of charts; in one type the relative aggregate saving is given versus the undrained shear strength, while the second type gives the additional shear strength of the subgrade versus the original shear strength. The additional shear strength is the apparent improvement of the subgrade due to the inclusion of geotextile. One of their

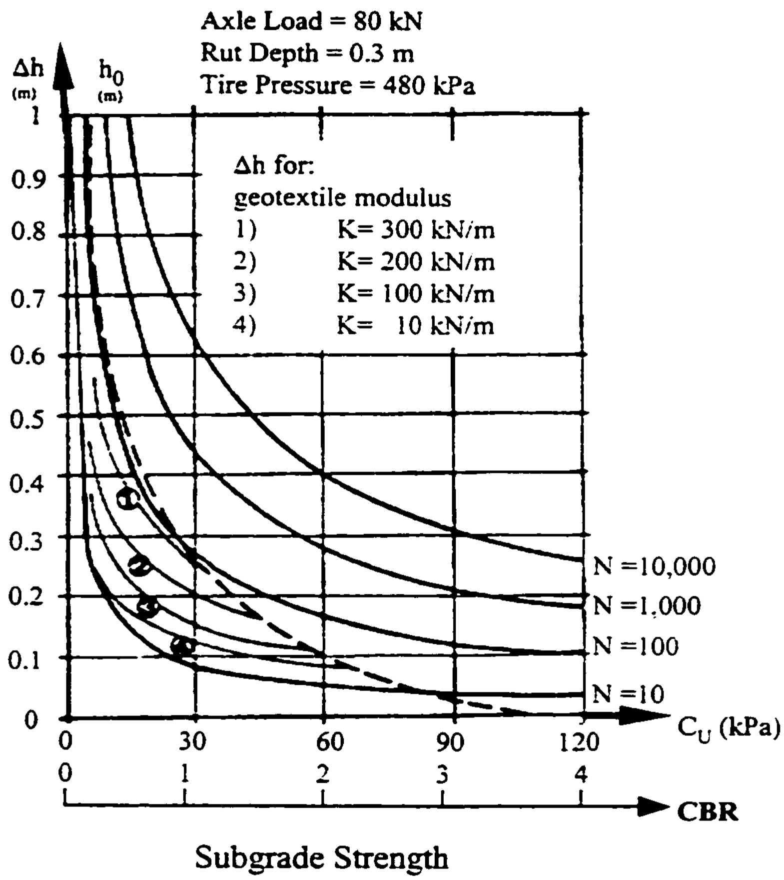


Figure 2.7: Aggregate thickness h_0 (case without fabric) and aggregate thickness reduction, Δh (case with fabric) as a function of subgrade strength (Redrawn from Giroud & Noiray, 1981)

conclusions was that the modulus of elasticity of the geotextile is the most determining factor in aggregate saving.

2.3.2 Model Tests

Aiban et al. (1998b) conducted an experimental program to assess the performance of a problematic sabkha soil from eastern Saudi Arabia and to improve its load-carrying capacity using different techniques. The sabkha samples were prepared in a large-scale stainless steel mold having a diameter of 750 mm and a height of 350 mm. The loading plate was chosen to have a diameter of 125 mm. The results clearly indicated the acute water sensitivity of sabkha, as evidenced by the complete loss of strength when samples were prepared at moisture contents other than the optimum value or when the sabkha was soaked. The results also demonstrated that the use of nonwoven geotextile improved the load-carrying capacity of the sabkha by up to four times that without geotextile.

Abduljauwad et al. (1994) have used nonwoven geotextiles to investigate the behavior of soil fabric aggregate sabkha subgrade systems, under both static and dynamic loading, considering as-molded and soaked conditions. The mold used in that study had a diameter of 320 mm and height of 420 mm and the diameter of loading plate was 60 mm. They reported that the incorporation of geotextiles in the SFA sabkha subgrade systems produced much higher resistance to static loads than similar systems without geotextiles for both as-molded and soaked conditions. In general, they concluded that with the incorporation of geotextiles, the SFA sabkha subgrade systems significantly improved the behavior of sabkha, particularly when the specimens were flooded with water. Their results indicated the excellent performance of the needle-punched nonwoven geotextile in SFA sabkha subgrade system.

Geotextiles have also been recently used in many construction projects along the coastal areas in eastern Saudi Arabia, for various purposes. Unfortunately, there is a lack of both construction details and long-term data on the performance of the SFA systems.

Kinney and Barenberg (1982) conducted a study in a two-dimensional model of geotextile-reinforced unpaved roads to evaluate the reinforcing effect of geotextile on the system. The model consists of lucite box 1.5 m long, 0.15 m wide and 0.92 m deep. The bottom 0.59 m of the box was filled with soft clay. A geotextile was placed over the clay and covered with 76 to 229 mm of aggregate ranging in size from 6 to 25 mm. The load was applied to a 100 x 150 mm flat plate on the surface of the aggregate. Displacements due to the applied load were measured and a procedure was developed for the analysis of the test data and projection of that data to field conditions using the Geotextile Tension Model (GTM) concept. GTM is a mechanistic model of the behavior of the geotextile in a soil-geotextile-aggregate system. It includes methods to determine the geotextile-induced shear and normal stresses, and the strain energy stored in the geotextile. They presented a technique, which can be used to calculate the tension in the geotextile at any point under the influence of the wheel load. Furthermore, an empirical correlation was established to estimate the shape of the surface of the geotextile in the rutted area. Test results showed that the presence of the fabric reduced the deformations in the systems.

Kinney (1982) performed small-scale laboratory tests to study the effect of a geotextile on a soil-geotextile-aggregate system. The setup consisted of placing clay at the bottom, then a geotextile and an aggregate layer was placed in a cylindrical mold and loading the surface with a circular plates with diameters ranging from 25 to 86 mm. The mold was 152 mm in diameter and 160 mm deep. Fifteen test series with a total of 61 tests were performed. The test results demonstrated that a geotextile disc slightly larger than the loading plate has a very significant reinforcing effect on the system, whereas, a disk identical in size to the loading plate does not appear to have any effect. The test results also indicated that the effect of a limited expanse of geotextile diminishes as the thickness of the aggregate increases.

Ramaswamy and Aziz (1982) studied the effect of using jute fabric in road construction application, especially when dealing with clayey sub-grades. A series of laboratory experiments were conducted using unconfined compression tests and CBR tests on samples compacted with and without fabric layers under saturated and unsaturated conditions. It was found that the jute fabric increases the CBR value and the stability of the soil and improves the bearing capacity and reduce the settlement of the sub-grade soil.

A major study concerning the use of geotextiles in SFA system is being conducted in the school of civil engineering at the Georgia Institute of Technology, Atlanta, Georgia (Robnett and Lai, 1981). In one phase of this study, a scale model test apparatus was used to evaluate relative performance characteristics of various SFA systems and to evaluate the relative significance of important parameters on the system performance. For this study 0.9 m diameter test pit with 38 cm thick, soft silty clay subgrade and dense-graded aggregate with layer thicknesses ranging from 13 to 33 cm was used. Repeated loading was applied using 15 cm diameter plate with contact pressure of 480 kPa (70 psi). Repetition rate of 20 per minute, and pulse duration of 0.2 sec was used. In order to develop insight as to the manner in which a variety of fabric properties influence SFA system performance, two test series were conducted as part of the study. In one series of model pit tests, different types of commercially available nonwoven fabrics, e.g. Typar spunbounded polypropylene fabric, Terram construction membrane, Supac nonwoven polypropylene fabric, Bidim, and three diagnostic membranes were tested under approximately the same conditions (e.g., aggregate thickness, subgrade strength, and loading). In the second series, different bases weights of Typar were similarly tested. In all cases, the primary measure of performance was surface rutting of the SFA system. Results showed that increased fabric modulus relates quite significantly to an increased rutting resistance.

Kinney and Barenberg (1980) have published performance data from small scale repeated load tests on SFA systems containing two fabrics designated M-1 and W-2. They reported the modulus of these fabrics as 53 kN/m (300 lb/in) and 193 kN/m (1100 lb/in.), respectively. They concluded that the higher modulus fabric improved performance as a result of greater confinement in the aggregate and the resultant greater "load spreading ability" of the aggregate. Barenberg (1980) has developed a design method for these two fabrics. Using this method, it can be shown that an approximately 10% reduction in aggregate thickness can be made if the high modulus geotextile is used in lieu of the low modulus one.

Robnett and Lai (1980), report a change in measured compressive stresses (measured with special pressure cells using diaphragm wire resistance strain gage) under simulated repetitive wheel loading when fabric is included in the aggregate-soil system. Pressure cells readings were obtained for surface rutting of about 3-4 inch under repetitive loading. Results show a reduction in the vertical compressive stress directly under the loaded area for the system that contains a fabric compared with an aggregate-soil system without a fabric. The reduction of the subgrade stress for the system that contains a fabric appears to be due to the membrane effect, although it could also be partly due to an increased load-spreading capability of the confined aggregate. As a result of the reduced subgrade stress, a reduction in the rate of rut formation in the subgrade for a given vehicular loading condition should be expected.

David et al. (1978) performed a study on a two dimensional model in a small box of 51 in (1295.4 mm) length, 18 in (457.2 mm) depth and 6 in (152.4 mm) width. The subgrade soil layer was 13 in (330.2 mm) thick, and the aggregate layer were 3 to 9 in (76.2 to 228.6 mm) thick. The repeated loads were applied to cause various levels of stress on the subgrade, and measurements of the permanent deformations and elastic rebound were taken during the tests. They concluded that deformations and rutting patterns are more localized and more severe in the systems without geotextiles.

2.3.3 Full-Scale Field Tests

In addition to the small-scale laboratory tests, several full-scale field testing programs have been performed. Some Of the most significant ones are described briefly below including the major conclusions drawn from each.

The results of a full-scale traffic test conducted by the Waterways Experiment Station, Vicksburg, Mississippi has been published (Webster et al., 1978). Two test sections; each containing a fabric and one reference test section without fabric were constructed. The subgrade was placed to have a CBR of about 1% in the upper 25 cm and a CBR ranging from 1.5% to 2.3% in the next 35 cm. A crushed lime stone layer, 35 cm thick was placed above this subgrade with the respective fabric in each of the two test sections. The two fabrics used were Bidim C-36 spun bounded polyester with modulus value of 380 lb/in and T-16 (a neoprene-coated, one ply, and woven nylon) with modulus value of 1720 lb/in. The performance of these three test sections subjected to traffic by a tandem axle, dual axle, and military dump truck is depicted in Figure 2.8. The T-16 fabric had a much higher modulus than the C-38 and thus, the influence of the higher modulus fabric is evident. For 900 vehicle passes the T-16 fabric section had about 50 mm of rutting while the Bidim C-38 section had about 180 mm of rutting. The section without fabric sustained only 200 vehicle passes at which a 150 mm (6 in.) of rutting resulted.

Giroud and Noiray (1981) have developed a design method, which requires fabric modulus and failure elongation as design inputs. For the design conditions of CBR=0.5, rut depth = 30 cm (9.12 in.) and N=100, this design method allows a reduction in aggregate thickness ranging from 25 to 40 percent for fabric modulus values ranging from 10 to 200 kN/m (960 to 1200 lb/in). They concluded that high modulus fabrics reduce the required amount of aggregate thickness.

Ruddoc et al., (1982) performed a full-scale experiment to investigate the effects of inclusion of fabric at the subgrade/sub-base interface in granular and bituminous-surfaced pavements. In that study, granular pavements of two thicknesses were laid on each of five fabrics over a clay subgrade, with two control sections. One fabric and one control sections were overlaid with dense bitumen macadam. Surface deformations, strains in all layers and vertical stress in the subgrade were measured under wheel loads up to 5300 kg. The results of the study showed that fabric had no effect on the performance of the macadam-surfaced pavement, but in the granular pavements, permeable fabrics caused reductions of permanent surface deformation and permanent subgrade strain.

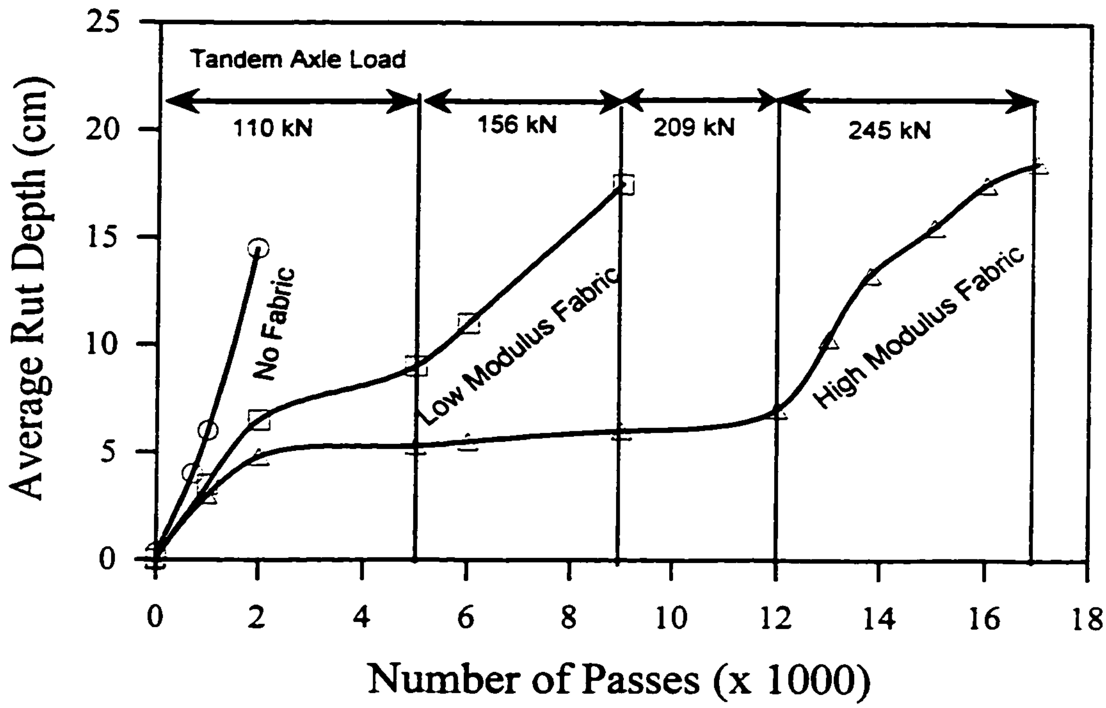


Figure 2.8: Rut Depth as a function of vehicle passes (Redrawn from Robonett & Lai, 1980)

Steward and Mahoney (1982) presented a brief program of a very extensive set of field tests performed by the U. S. Forest Service near Quinault, Washington. The test sections included many types of fabrics over a subgrade with a CBR of about 1%. The thickness of the granular layer was based on the Forest Services design procedure. The fabric was placed by unrolling it over an extremely irregular surface, which was not completely stripped of all organic matter. The fabric was therefore stretched irregularly during installation. The road was narrow and lightweight traffic was allowed. Measurements included vertical settlement, vertical pressure and fabric strain. Very little rutting was experienced. No fabric strains were detected. They indicated that the fabric properties should not enter into the design.

Chapter 3

EXPERIMENTAL PROGRAM

The experimental program of this study consisted of two parts. The first part consists of routine characterization tests on both the sabkha subgrade soil and the steel slag aggregate (SSA), which constitute the graded base material. The second part, which is the main one, consists of testing a model of Soil-Fabric-Aggregate System under both static and repetitive loading. The primary variables were:

1. Moisture condition
2. Thickness of SSA base layer
3. Load type
4. Grade of geotextile
5. Lateral extent of geotextile

Details of the entire program will be discussed in the following sections.

3.1 Research Methodology and Work Plan

In order to achieve the proposed objectives, the work was planned according to the following two steps:

1. Material Collection and Characterization
2. Large Scale Geotextile Testing Program

3.2 Material Collection

3.2.1 Sabkha Soil Collection

The sabkha soil used in the testing program was collected from Ar-Riyas area. The Ar-Riyas site is located at about 20 km southwest of the industrial city of Jubail, eastern Saudi Arabia. The location of Ar-Riyas site is shown in Figure 3.1. At Ar-Riyas site, the surface was observed to be covered with non-crystallized halite, which extends 30 to 70 mm in thickness. The ground water table was found at depth of 200 mm. The sabkha soil was retrieved from all layers above the ground water table excluding the salt crust. Thereafter, these samples were brought to the geotechnical laboratory at KFUPM for testing. The materials were first spread on plastic sheets outside the laboratory for air-drying. Plastic hammers were used to gently break the soil lumps to make them passing ASTM sieve # 4. Finally, the whole soil was thoroughly mixed and stored in plastic drums until testing. Figure 3.2 shows the sabkha soil pile after crushing and thorough mixing. Its worth mentioning that the air drying process took more than one month.

3.2.2 Geotextiles Collection

In this study, non-woven, needle-punched, polypropylene geotextiles were used. The most important property of a geotextile in reinforcement applications is its tensile strength. The non-woven needle punched geotextiles have significantly improved the stress-strain behavior under confinement (Koerner, 1998). One special characteristic of polypropylene geotextile is its non-sensitivity to chemical products of low and moderate

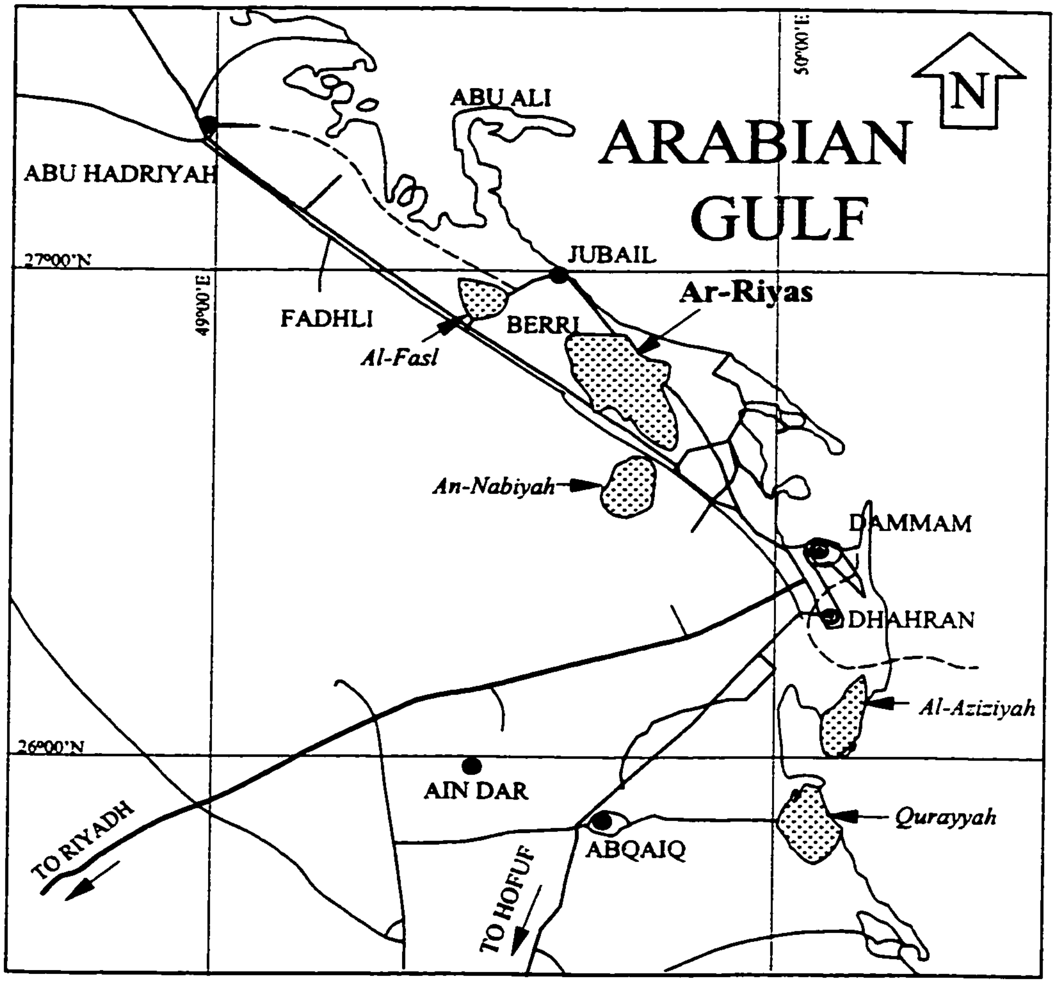


Figure 3.1: Map of Eastern Saudi Arabia showing the location of Ar-Riyas sabkha (Aiban et al., 1999)

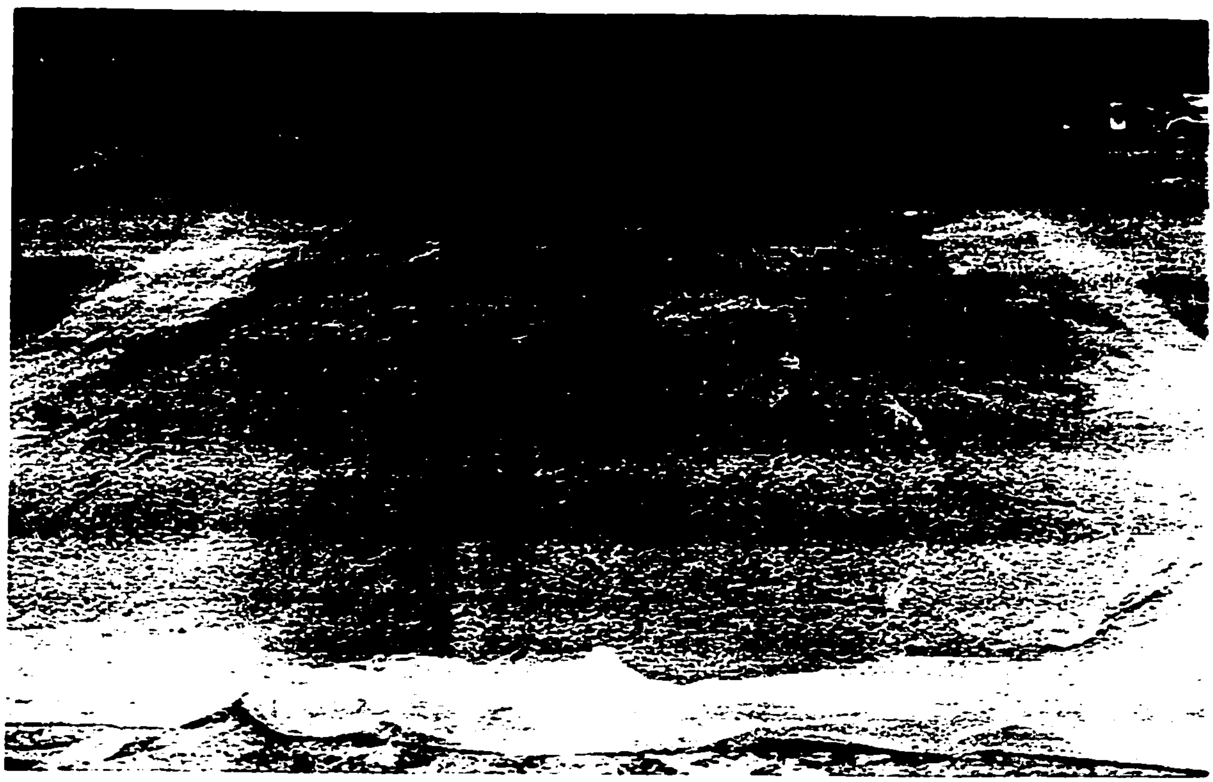


Figure 3.2: Sabkha soil after crushing and homogenization

concentration. Theses types of geotextile are manufactured locally in Dammam, Saudi Arabia, and extensively used in the region for reinforcement, separation and filtration purpose. In this research program, three different geotextile grades were used. These were labeled as A-400, A-300 and A-140. These geotextiles have mass per unit area of 400 g/m^2, 300 g/m^2 and 140 g/m^2, respectively.

3.2.3 Steel Slag Aggregate (SSA) Collection

The steel slag aggregate (SSA) used in this study was collected from the steel manufacturing company (Hadeed) located in Jubail. Grain size distribution and specific gravity test were performed on the SSA. The results of theses tests are presented in Chapter 4.

3.3 Characterization of Sabkha Soil

Some characterization tests were performed in the geotechnical laboratory of the Civil Engineering Department to determine the geotechnical properties of the sabkha. In addition, X-ray Diffraction (XRD) analysis was carried out to identify the mineralogical composition of the sabkha. The tests performed are listed below and the results of theses tests are presented in the results and discussion in Chapter 4.

3.3.1 Grain Size Distribution

Grain size distribution (GSD) is the main test used to classify soils. Grain size distribution or the soil gradation is the distribution of particle sizes expressed as percent of the total weight. Gradation is determined by the sieve analysis, that is, by passing the material through a series of sieves stacked with progressively smaller openings from top to bottom and weighing the material retained on each sieve. For Ar-Riyas sabkha washed sieve analysis was done according to ASTM D422. The Samples were washed with both distilled water and sabkha brine. A set of sieve including ASTM No. 10, 20, 30, 40, 60, 100, 140 and 200 sieves was used for sieve analysis. Distilled water dissolves some of the salts in the sabkha matrix and will therefore, alter the plasticity of the soil. On the other hand, the sabkha brine will increase the salt content of the material (Aiban et al. 1999). Therefore both sabkha brine and distilled water were used to obtain the grain size distribution and the Atterberg limits; however, the classification was totally based on the tests conducted using sabkha brine.

3.3.2 Atterberg's Limit

Liquid limit and plastic limit are important to classify the soil if more than 50% of its particles are passing ASTM sieve No. 200. For the sabkha soil passing sieve No. 40, the plastic limit and liquid limit tests were performed according to ASTM D 4318. Both sabkha brine and distilled water were used for these tests due to the high dependency of the results on the fluid used for the tests (Aiban et al. 1999).

3.3.3 X-ray Diffraction Analysis

X-ray Diffraction (XRD) analysis was carried out to identify the mineralogical composition of the sabkha. The test was performed in the central analytical and materials characterization laboratories in the Research Institute at KFUPM. The XRD was performed using a Philips PW 1700 automated diffractometer with a monochromator and sample spinner. Diffraction Patterns were generated on a vertical goniometer attached to a broad-focus X-ray tube with a copper target operating at 45 kV and 30 mA. The analysis is computer assisted so that the interplanar spacing values can be corrected for the instrument error function with reference to silicon standard. The two sabkha soil samples were powdered with an agate pestle and mortar and sieved through a #100 (150 μm) sieve, so that many grains come into orientation and the quality of the diffraction pattern is greatly improved. A homogenous sample of this powder was packed into a sample holder and scanned. The phase identification process involves matching peak intensity and peak position patterns by the patterns of the different standards prepared by the Joint Committee of Powder Diffraction Data Service (JCPDS). This way the different minerals present in the sample were determined.

3.3.4 Moisture-Density Relationship

Proctor compaction test was used to provide a relationship between the molding moisture content and the dry density of the soil. Two types of Proctor tests are used in practice, the standard Proctor test (ASTM D 698) and the modified Proctor compaction test (ASTM D 1557). The use of modern heavy compacting equipment in the field necessitates the use of the modified Proctor compaction test. Therefore, the modified Proctor test was adopted in this investigation to determine the moisture-density relationship for the sabkha soil.

3.3.5 California Bearing Ratio (CBR) Test

California Bearing Ratio (CBR) test is an empirical test, which has been commonly used in the structural design and evaluation of pavements. There is no direct relation between the CBR value and the shear strength parameters, such as the cohesion and angle of internal friction. In addition, the test is static while the loads generated by the traffic wheels are dynamic in nature. The results can only be used for the method of design for which the test was devised. This test can also be used to compare different materials. In spite of these limitations, the test is recognized worldwide because of its simplicity and applicability. Therefore, it can easily be used to judge the material for use in pavement construction. The samples prepared for the moisture-density relationship were subjected to CBR testing procedure (ASTM D1883). The California-Bearing Ratio was conducted for samples prepared at different moisture contents to assess the moisture sensitivity of the CBR values for the sabkha. Two sets of CBR tests were performed, one for the samples as they are (as-molded) while the other was performed after soaking the samples for 96 hours. This was done to illustrate the effect of soaking on the CBR values.

3.4 Testing Program

The objective of this experimental program was to determine the difference between the response of identical systems, with and without geotextiles, in as-molded and in soaked conditions. Several variables and their effects were considered in this study. These variables include:

1) Grade of geotextile: Three grades of geotextile were used in this study having different values of tensile strength and mass per unit area.
2) Static and dynamic loading: One type of static loading and three different levels of dynamic loading 50 kPa, 100 kPa, 200 kPa were used.
3) Moisture conditions: two types of moisture conditions as-molded and soaked were used.
4) Thickness of SSA granular base: Three base thicknesses 33 mm, 65 mm, and 98 mm were used.

5) Lateral extent of geotextile: Four different sizes of Geotextile diameter were used in order to determine its effect on the response of the system.

In addition, the sabkha was treated with different percentages (5, 7, and 10%) of Portland cement and the performance was compared to that of sabkha-geotextile system under similar loading conditions. This research program was carried out according the flow diagram shown in Figure 3.3.

The factorial design matrix and sample coding of the different samples is presented in Table 3.1. Some samples were tested under static loading while some other samples were subjected to repeated loading. It is also seen from the factorial design, that when studying the effect of one variable on the performance of the system, the rest of the variables were kept constant. For example, the effect of base thickness was studied for one grade of geotextile at one level of stress. The factorial design (Table 3.1) consists of different testing conditions, which includes three thicknesses of the base, three levels of deviatoric stress and three grades of geotextiles. The procedure and coding for samples in load testing is as follows:

1. Each test was assigned a number in the form of a notation code. Table 3.1 shows the designated sample codes for the different test conditions. For example, in this sample code "P100GA400H65W", 'P100' means that the sample subjected to the deviatoric (pulse) stress level of 100 kPa; 'GA400' indicates that A-400 geotextile was used while 'H65' presents the thickness of the base which is 65 mm and 'W' indicates that the condition of the test is soaked (or wetted), where 'D' presents the dry (as-molded) condition in other tests. The letter S is used to denote static loading.

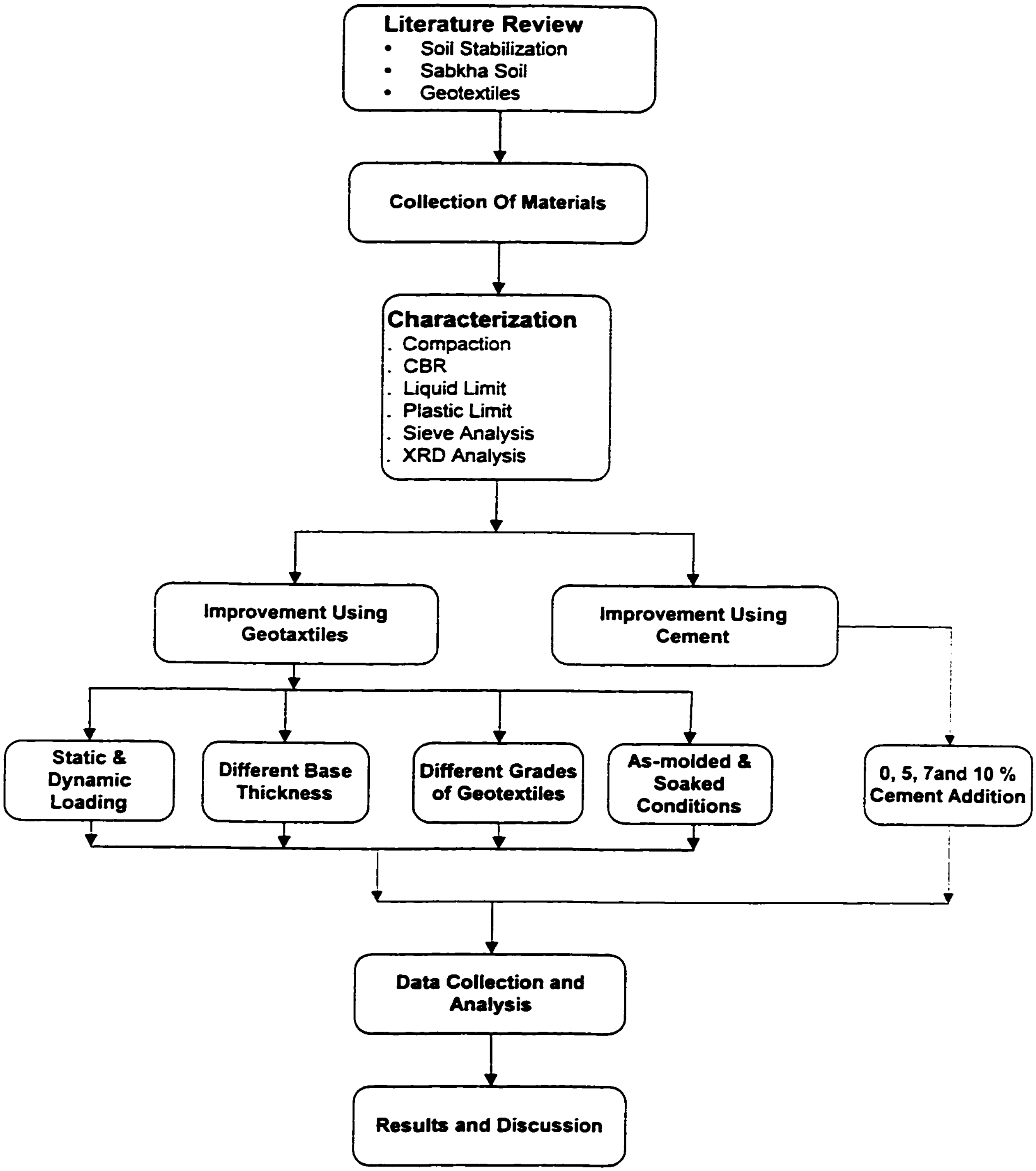


Figure 3.3: Flow diagram showing the research program

Table 3.1: Experimental design matrix and coding designation for the various SFA systems

Test Condition	Deviator Stress (kPa) / Geotextile Grade	Base Thickness (mm): $H_1 = 33$	$H_2 = 65$				$H_3 = 98$
		$P_2 = 100$ kPa	Static Load	$P_1 = 50$ kPa	$P_2 = 100$ kPa	$P_3 = 200$ kPa	$P_2 = 100$ kPa
As-molded	Without Geotextile (G_0)		SG0H65D		P100G0H65D		
	Geotextile A-140						
	Geotextile A-300		SG300H65D				
	Geotextile A-400				P100G400H65D		
Soaked	Without Geotextile (G_0)	P100G0H33W	SG0H65W	P50G0H65W	P100G0H65W	P200G0H65W	P100G0H98W
	Geotextile A-140		SG140H65W		P100G140H65W		
	Geotextile A-300		SG300H65W				
	Geotextile A-400	P100G400H33W	SG400H65W	P50G400H65W	P100G400H65W	P200G400H65W	P100G400H98W

Test Condition	Cement Content	Base Thickness; $H_2 = 65$mm: Static Load
Soaked	5%	SC5G0W
	7%	SC7G0W
	10%	SC10G0W

D = As-molded Samples (dry)
W = Soaked Samples (wet)
SC = Cement Content
P = Pulse Loading
S = Static Loading
H = Thickness of SSA Layer
G = Geotextile

2. The number of load repetitions and the measured permanent deformation were recorded in a computer through data logger. All permanent deformation readings are plotted against the number of load repetitions for dynamic loading. In case of static loading, permanent deformations are plotted against load required for corresponding deformation.
3. The Symbols used in the graphical presentation of results are just to differentiate the curves. These symbols do not represent the actual number of data points.

3.5 Large-Scale Testing Mold

In this study, a large-scale setup was used. This setup consists of a large stainless steel mold having a diameter of 750 mm and a height of 450 mm with a wall thickness of 6.4 mm. The mold rests on a square stainless steel plate having the dimensions of 1100 × 1100 mm and 16.5 mm in thickness. The mold was fabricated at KFUPM central workshop, to conduct representative tests on sabkha soil reinforced with geotextile or treated with chemicals. The large size mold was used in order to resemble the field conditions. The diameter of mold was about five times greater than the loading plate diameter (d_p=130 mm) to avoid the side restrain effect of mold walls and to provide enough anchorage of the geotextile to avoid the slippage of the geotextile under the action of forces. Stainless steel material was used in the setup because of the chemical aggressivity of the sabkha. In order to soak the samples, four holes were provided in the lower portion of the mold, which were connected to an upper reservoir containing the soaking fluid (usually distilled water). The bottom reservoir was provided to maintain constant water level during the soaked samples tests. The setup is schematically shown in Figure 3.4. A photographic view of mold is shown in Figure 3.5.

3.6 Sample Preparation

The samples for the geotextile testing were prepared in the large-scale mold. The sample preparation includes mixing of sabkha at the desired moisture content, compacting the mix, placing a layer of geotextile over the subgrade (i.e. sabkha) soil and placing the base material (i.e. Steel Slag Aggregate).

The sample preparation consists of the placement of a 20 mm layer of coarse sand filter in the bottom of the mold. A layer of geotextile was then spread over the sand, which acts as a separator, between the sand and sabkha layer, and as a filter across which water flows in an upward direction during soaking of the sample. The sabkha soil was mixed at the required amount of water in a large mechanical mixer as shown in Figure 3.6. A known amount of soil was placed in the mold and compacted to the required dry density, using the static compaction method by means of a large hydraulic jack, which acts against a strong reaction beam. The whole set-up is shown in Figure 3.7. The soil was compacted in three lifts having thickness of 70, 60 and 70 mm. The compaction of these layers was one of the most important tasks of conducting SFA test. To obtain a homogeneous, subgrade with constant properties from test to test, the soil had to be mixed uniformly at constant water content and computed in a uniform manner. Therefore, the sabkha soil was compacted to 90% maximum dry density but at the optimum moisture content. The 90% dry density was found to be 1.62 g/cm^3 while the optimum moisture content was equal to 14%. These values were obtained by the Proctor

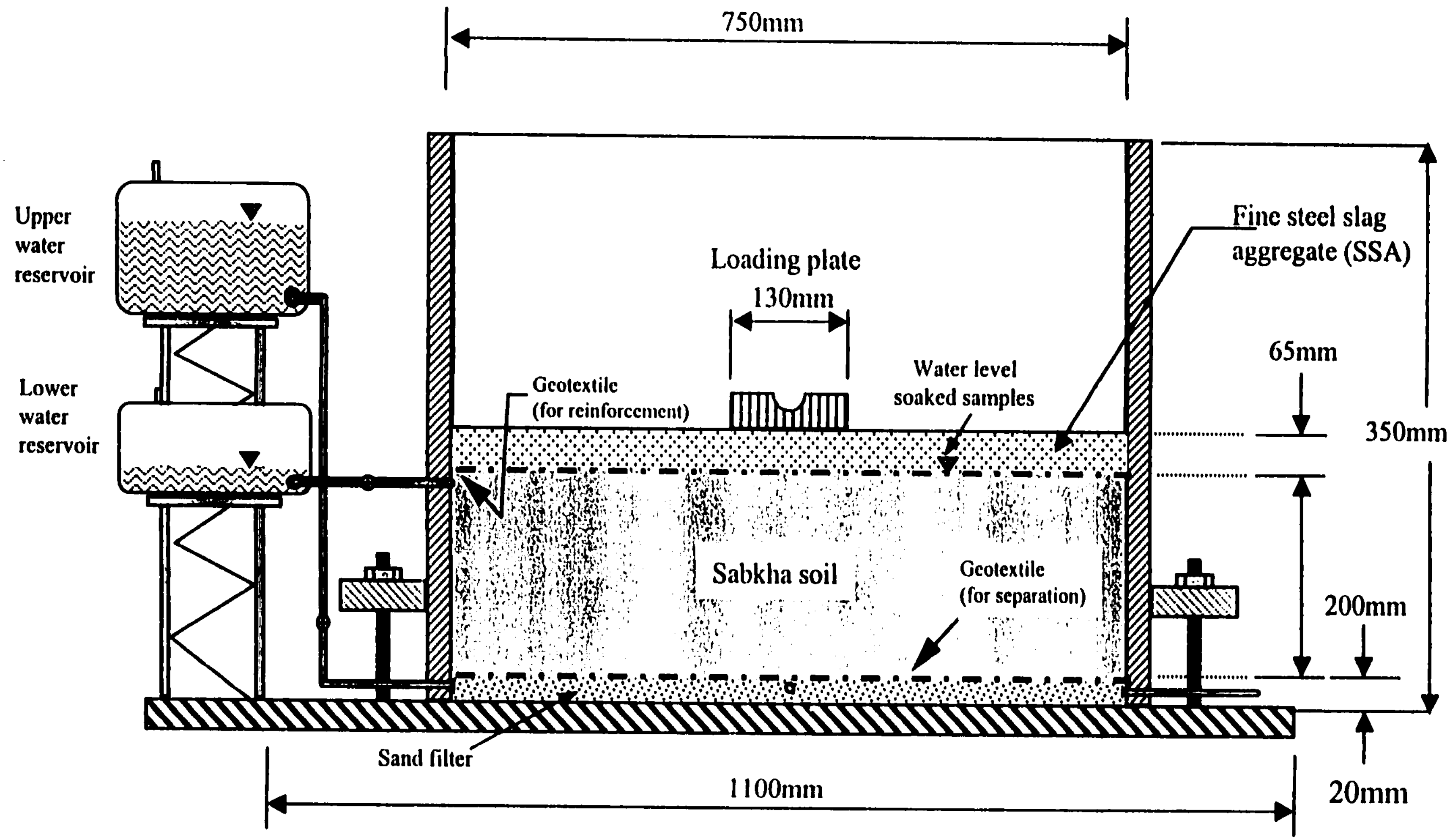


Figure 3.4: Schematic diagram of the experimental setup for the sabkha-geotextile-aggregate (SFA) system

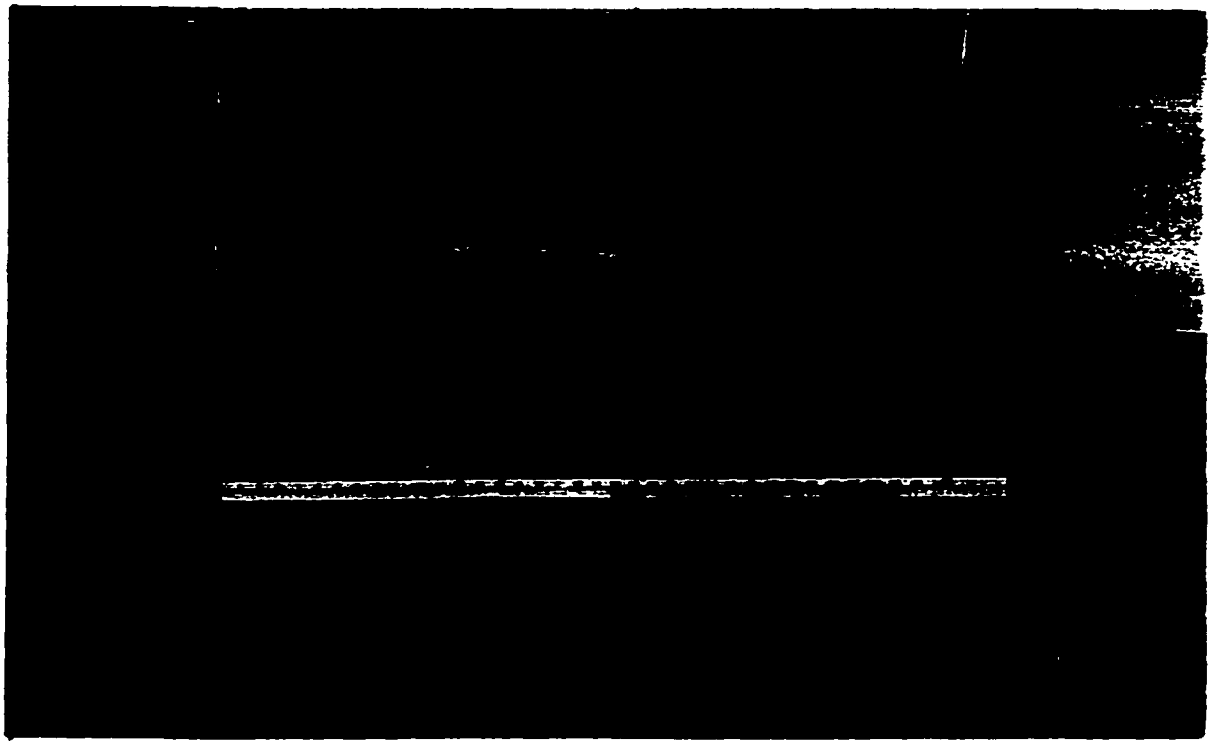


Figure 3.5: Large-scale stainless steel mold for SFA samples testing (the stick is 1 m long)

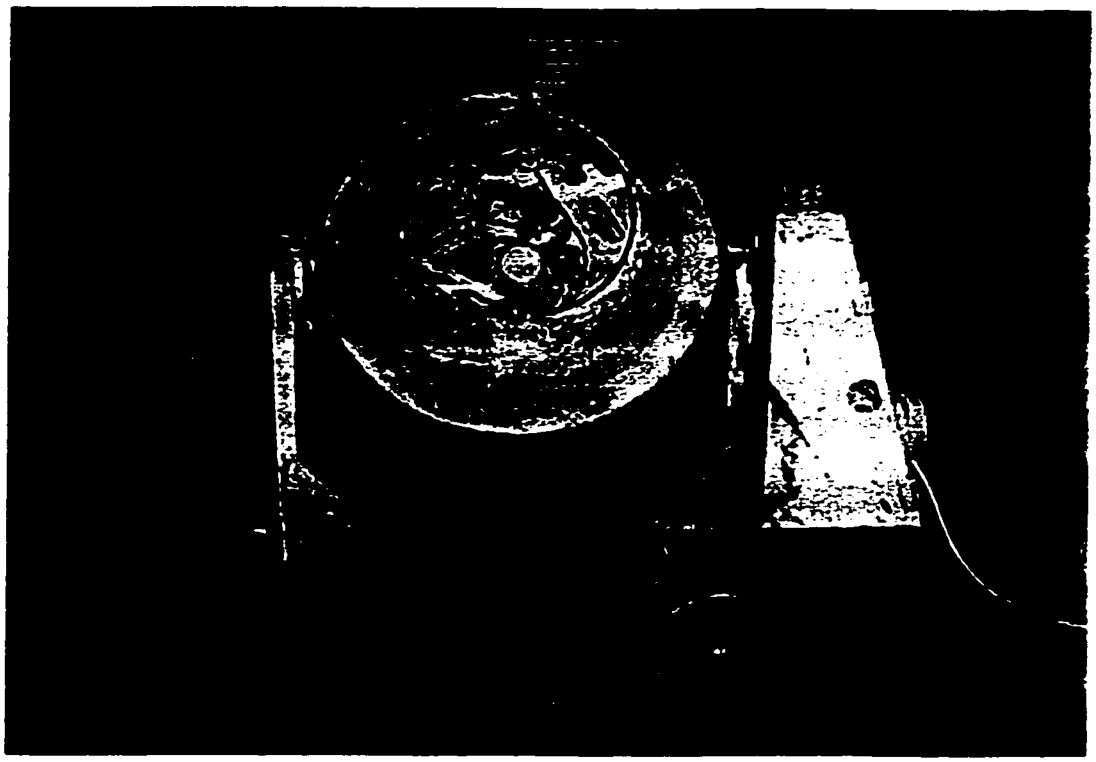


Figure 3.6: Mechanical mixer used for sabkha soil mixing

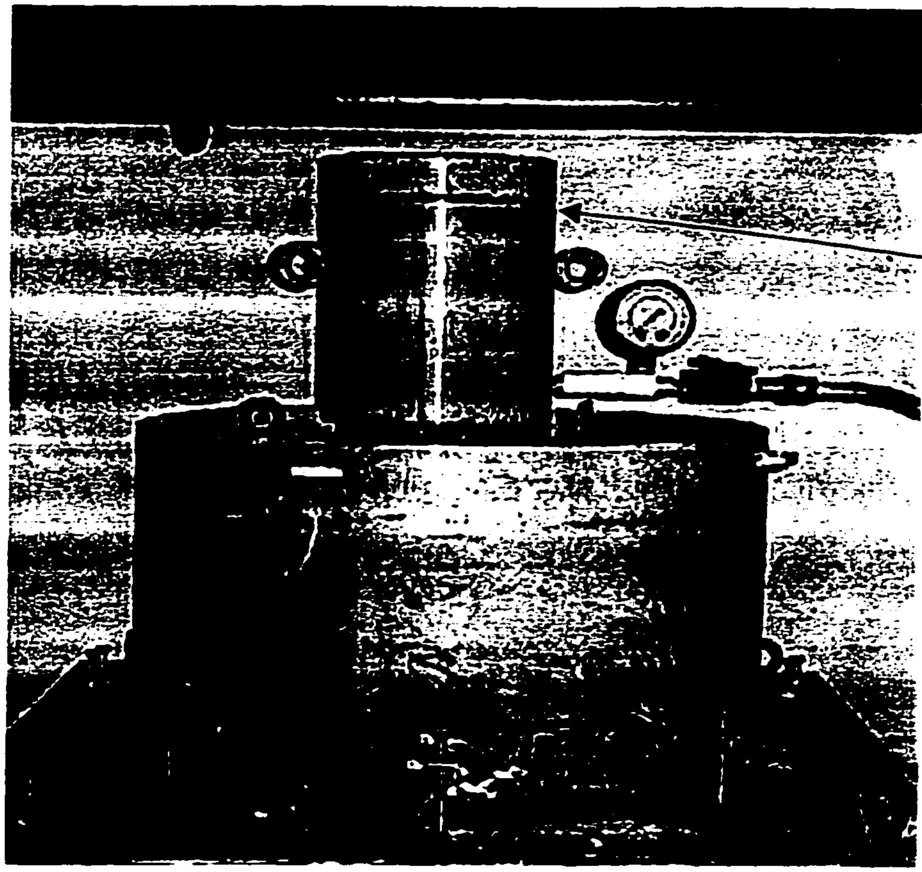


Figure 3.7: Set-up for static compaction of sabkha samples

will be discussed in chapter 4. The geotextile was cut into circular shapes of 750 mm diameter and then placed on the top of the compacted sabkha soil. On top of the geotextile layer, a pluviated-granular layer of SSA was used as a granular base coarse. The thickness of slag layer was variable. SSA was pluviated from a height of one meter using a pluviation cone having an opening size of 15 mm, as shown in Figure 3.8. The samples to be tested under soaked conditions, were soaked through the four holes made in the lower portion of the mold, which are connected to a reservoir containing the soaking fluid.

3.7 Soaking Process

According to the testing program, some samples were tested under soaked condition. The main feature of the soaking process was to permit the water to flow upward (from the bottom) through the compacted sample. For this purpose, four holes were provided in the lower portion of the mold, which were connected to a top reservoir containing distilled water. The water was allowed to enter the mold under a constant head of 1.5 m to soak the sample. Full soaking is achieved when the water inside the mold becomes at or just above the top surface of the specimen (top of SSA layer). Complete soaking takes at least 8 to 10 hours. After soaking the sample, the valve connecting to the top reservoir was closed and the valve of the lower reservoir was left open to maintain a constant water level in the sample. The soaking of sabkha using distilled water dilutes the salts in the sabkha and since the sabkha samples are reused for some tests, there is a need for salt concentration adjustment. This is done by measuring the amount of salt in the sabkha and adjusting the deficiency by adding an appropriate amount of sabkha brine to the soil

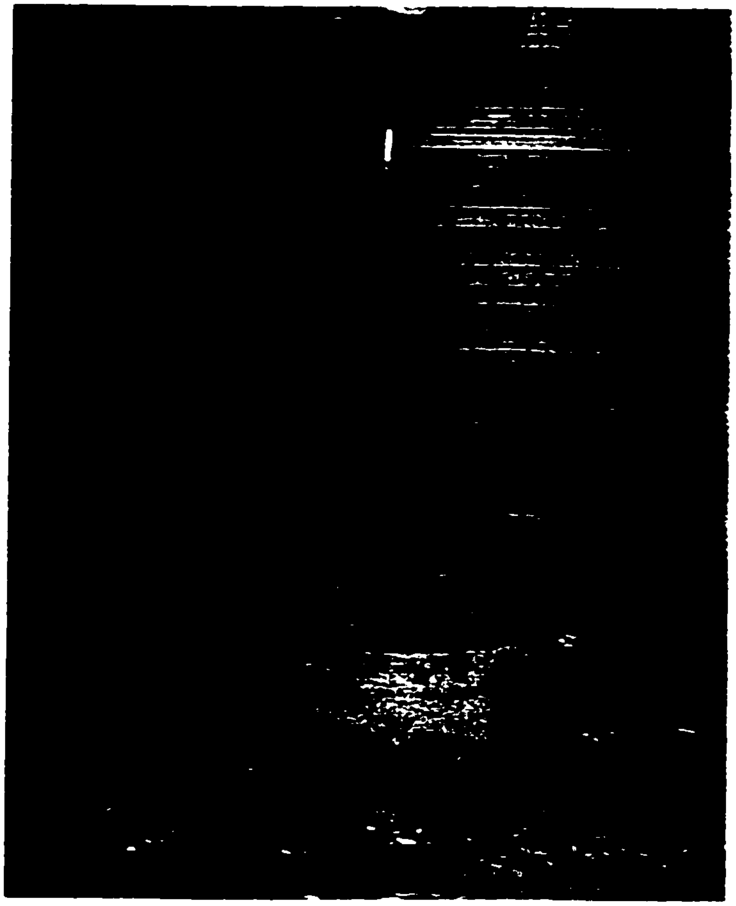


Figure 3.8: Pluviation of the Steel Slag Aggregate (cone at the top and the mold on the floor)

before compaction. The salt concentration is usually measured using total dissolved solids (TDS) test. The adjustment requires few trials, before reaching the correct concentration.

3.8 Loading Systems

The loading process is one of the main parameters in the study. All the samples were subjected to either static or dynamic loading while varying the desired variables such as: i) thickness of the base, ii) grade of geotextile, and iii) soaking effect. The details of loading systems are given in the following sections.

3.8.1 Static Loading Tests

Some of the samples were tested under static loading condition. The load was applied through an electric motor connected to the loading system, which in turn transfers the load to the loading plate on top of the sample. The loading system consists of gear driving a piston. The gear is operated by an electrical motor. The system is considered constant deformation rate system. A load cell was provided between the loading shaft and the loading plate. The load cell was connected to the computer through a data logger for data recordings. In this research, a constant deformation rate of 1 mm per minute was selected. Figure 3.9 show the motor connected with the loading system.

3.8.2 Repeated Loading Tests

Figure 3.10 shows the schematic repeated loading system used in this study. This system was assembled in the soil laboratory of the Civil Engineering Department at KFUPM. It includes a loading frame, an air-powered loading apparatus and a control system from

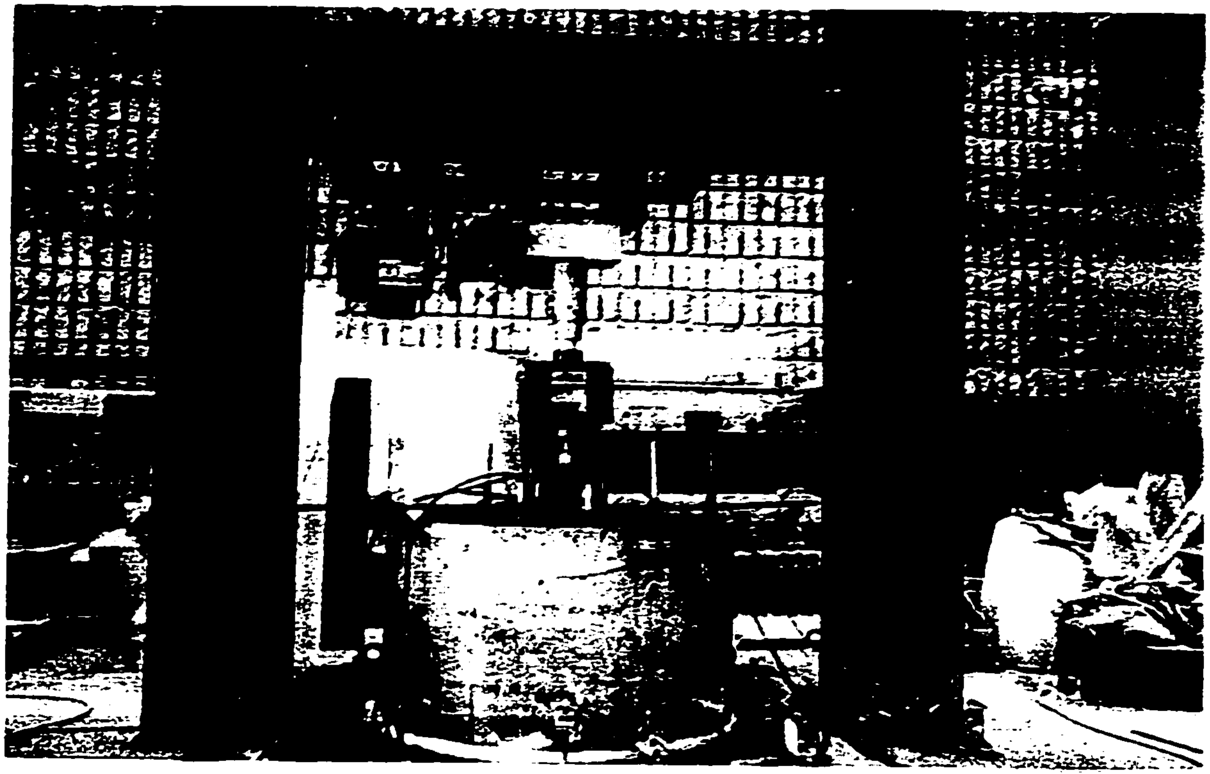


Figure 3.9: Set-up and electric motor used for static loading

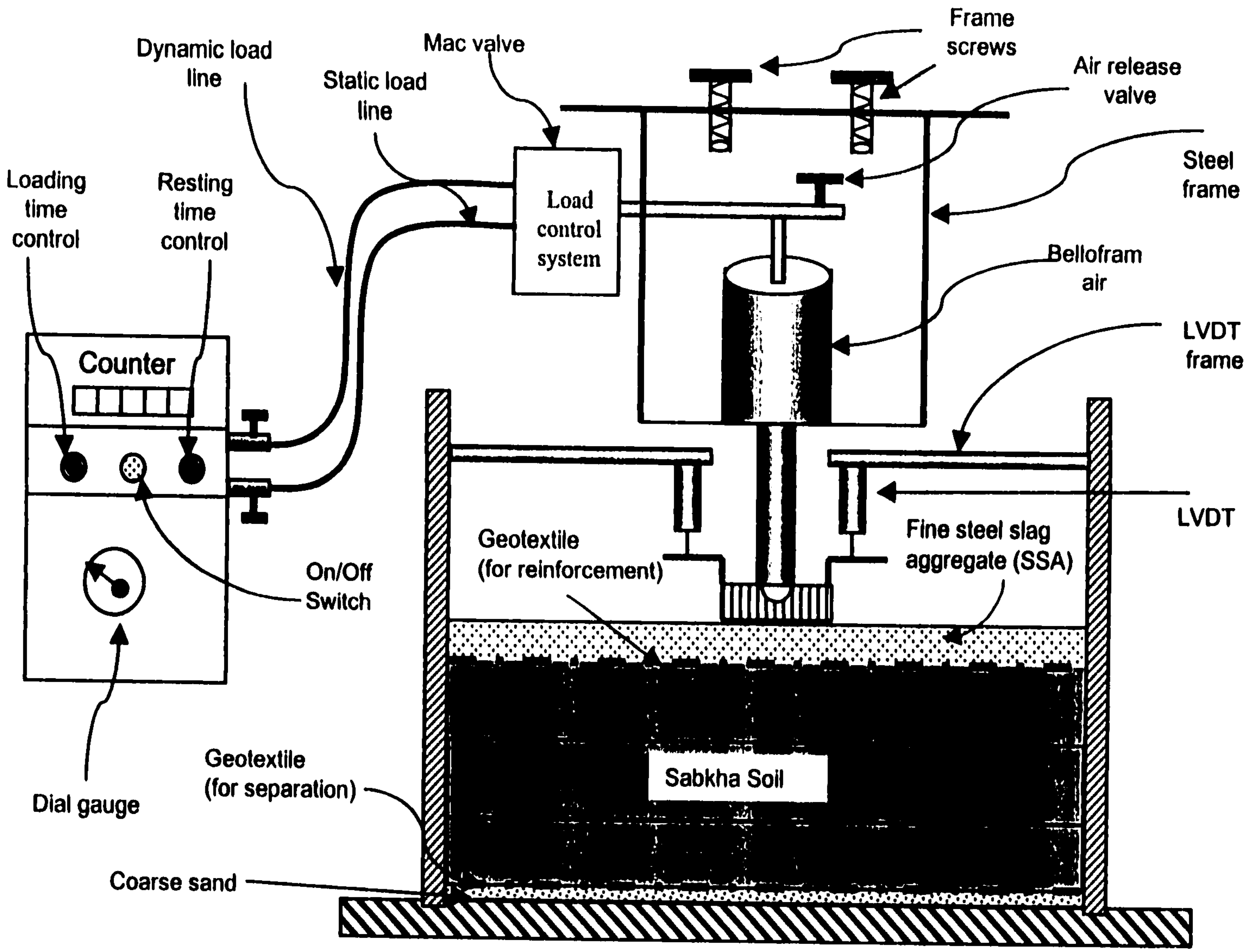


Figure 3.10: Schematic diagram of the experimental setup for dynamic loading

which dynamic load can be controlled. The loads are applied using an electro-pneumatic system. It consists of a pressurized air cylinder, a shuttle valve and a three-way solenoid valve. The air cylinder was placed on top of the loading frame. The air from this cylinder pushes the piston at which load cell is attached which in turns pushes the loading plate placed at the center of the specimen at its surface. Operation of the solenoid valve requires a 110V power supply, a pilot air supply, and a main air supply. The pressurized cylinder can be activated by the three-way solenoid valve line. The three-way solenoid valve regulates airflow to the air cylinder and is designed to allow the line of highest pressure to flow into the air cylinder. Static load and dynamic load pressure lines, and electrical signal to the solenoid valve are monitored from the control system.

The control system is composed of the following:

i) A Pneumatic system, which is able to supply air to the cylinder.

ii) Precision air regulators and pressure gages to provide good control of the static and dynamic pressure lines.

iii) Two timers (pulse interval and pulse duration) to control the electrical signal to the Mac valve.

iv) A counter to record the number of pulse loads.

In all dynamic tests, seating load of 10 kPa was applied to hold the piston on the loading plate. The dynamic load duration was fixed at 0.15 seconds and the load frequency at 60 cycles per minute. All tests were performed at room temperature.

3.9 Deformation Measurement

Four Linear vertical displacement transducers (LVDT) were installed on special holders extending outside the periphery of the loading plate. The LVDT's are equally spaced around the loading plate as shown in Figure 3.11. The LVDT's were used to record the deformation produced by the plate. A load cell, attached to a shaft above the loading plate was used to measure the applied load. These strain transducers and load cell were connected to a computer through a data logger.

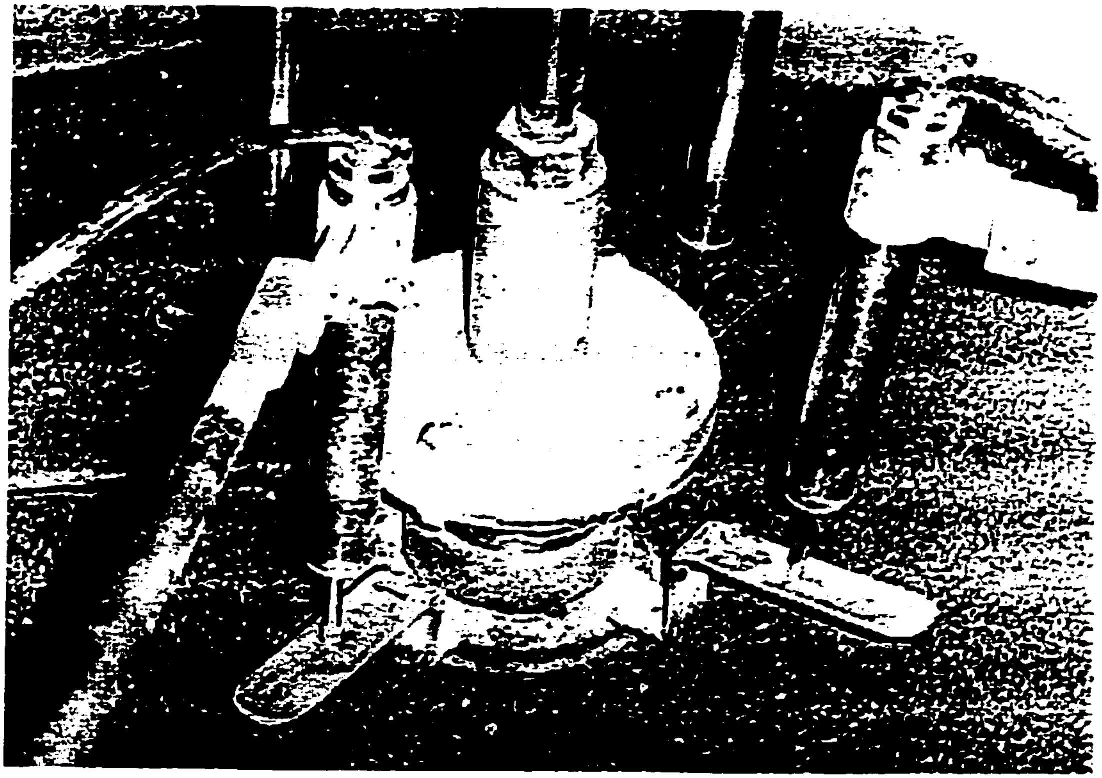


Figure 3.11: Linear vertical displacement transducers (LVDT) used for recording deformation

Chapter 4

RESULTS AND DISCUSSIONS

4.1 General

This chapter present the results obtained from the tests performed on plain and improved sabkha samples, during the course of this experimental program of the thesis, as well as the discussion of these results. The main phase of the experimental program is the load-carrying capacity tests performed to assess the effect of using geotextiles and cement on the behavior of sabkha subgrades. However, some routine tests were performed to characterize the sabkha soil and the SSA. The results can be grouped into two categories:

1. Characterization results
2. Load-carrying capacity results

4.2 Characterization Tests

Some general tests were performed on the retrieved sabkha for finding its physical and chemical properties. However, the properties of the geotextile were taken from the supplier's specifications without performing any test in the Civil Engineering laboratories. The results are explained in the following sections.

4.2.1 Sabkha Characteristics

4.2.1.1 Grain Size Distribution

Washed sieve analysis was performed for Ar-Riyas sabkha. Washing was done using both distilled water and sabkha brine. The results showed that the soil consists of fine-grained particles as shown in the grain size distribution curve in Figure 4.1. It was found that the percentage passing ASTM sieve No. 200 is 97 when using distilled water, and 92 when using sabkha brine in the washing process, this lead to a difference of 5%. This difference in the fine content of soil is mainly due to the dissolution of sabkha salts in the distilled water. It should be noted that the difference was expected to be more than 5% since the sabkha soil has more than 20% halite (NaCl) by weight. However, it seems that washing with sabkha brine may have washed some of the salts also but this observation need further testing.

4.2.1.2 Atterberg's Limits

The liquid limit values showed distinct and large difference in the case when either sabkha brine or distilled water was used. The liquid limit was 33% and 42.5% for sabkha brine and distilled water, respectively, the difference being 9.5% as shown in Figure 4.2. Similar behavior was observed when the plastic limit was determined. The corresponding plastic limit values were 20.4% and 26.3% for sabkha brine and distilled water, respectively. Thus, the plasticity index (PI) is 12.6 for sabkha brine and 16.2 for distilled water. The soil was classified as CL representing clay of low plasticity according to Unified Classification System and as A-6 representing clayey soil and rated fair to poor as a subgrade, according to AASHTO classification system. The values are summarized

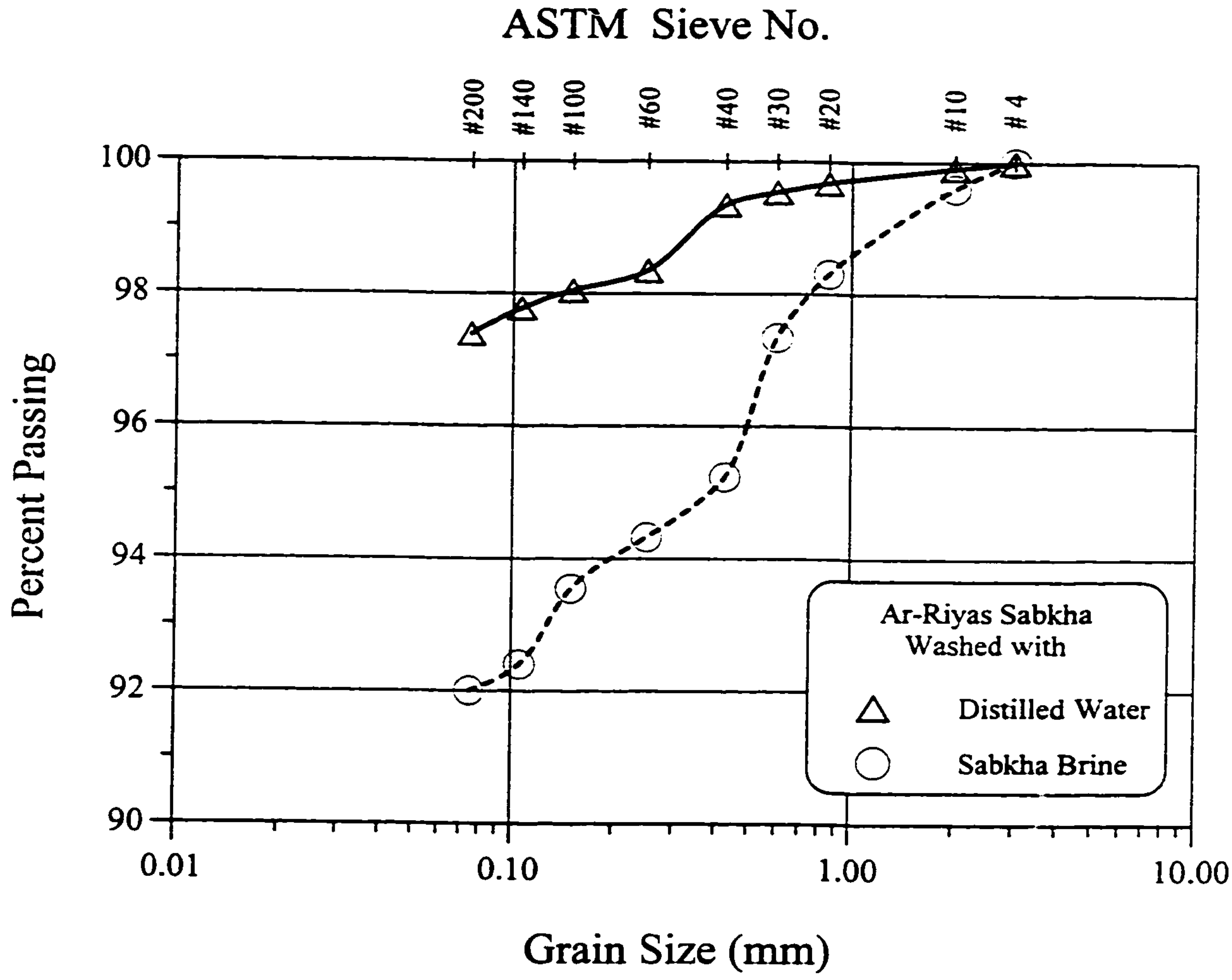


Figure 4.1: Grain-size distribution of Ar-Riyas sabkha soil

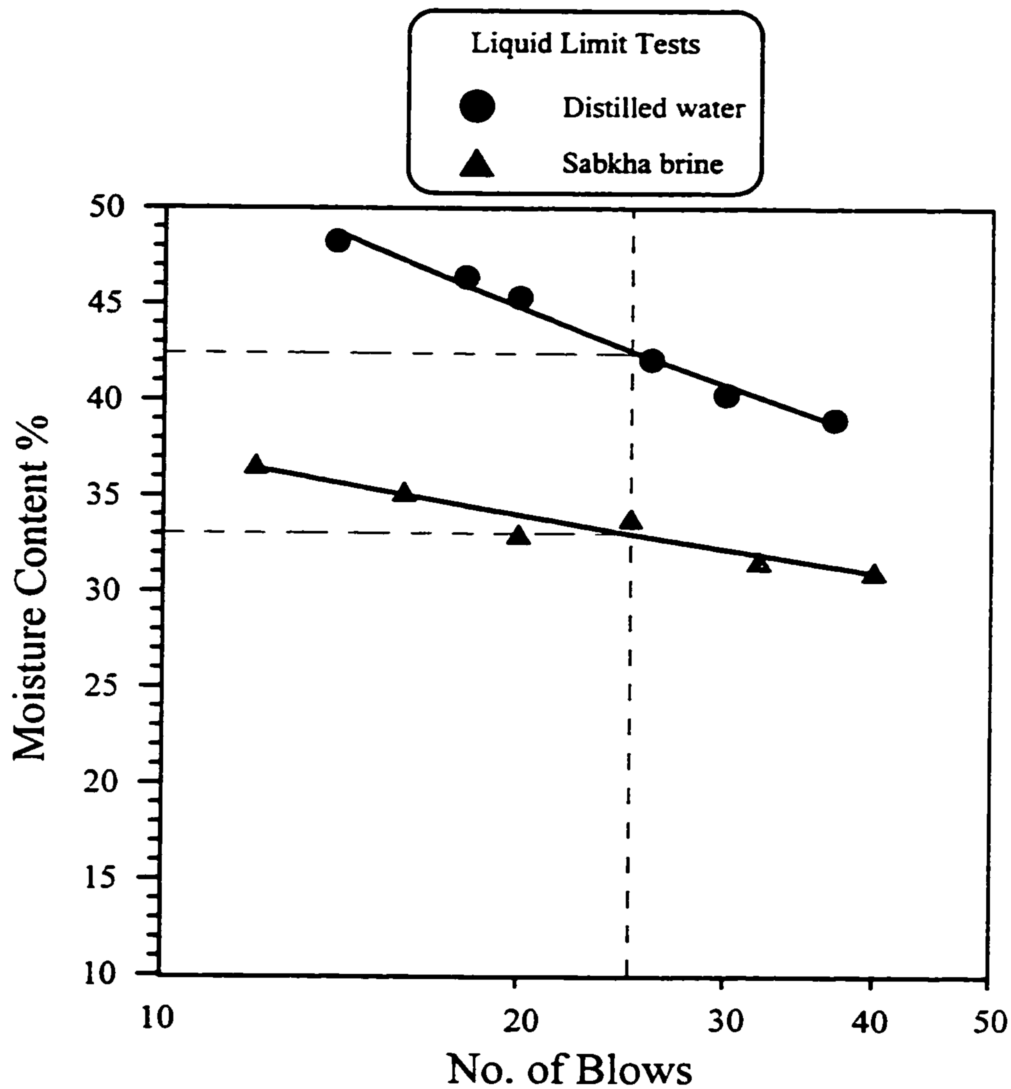


Figure 4.2: Liquid Limit (LL) curves for Ar-Riyas sabkha soil

in Table 4.1. The higher liquidity and plasticity ascribable to the use of distilled water in the tests, as compared with sabkha brine, is attributable to the fact that sabkha brine contains soluble salts that constitutes about 20% (by weight) ob the sabkha brine. Theses salts will precipitate upon drying of the sample after conducting the liquid limit and plastic limit test and thus will increase the solids (or dry weight). Furthermore, when using sabkha brine the amount of fluid that evaporates is less than that when distilled water is used. This will ultimately decrease the weight of water and increase the weight of solids when sabkha brine is used. Accordingly, the values of liquid limits and plastic limits will be less than the corresponding ones when distilled water is used (Aiban et al., 1999).

4.2.1.3 X-ray Diffraction Analysis

The summary of the XRD analysis results is presented in Table 4.2. The number in the last column of the table represents approximate weight fraction of the phase in percentage. It is clearly seen that Anhydrite constitutes about 88% of the sabkha soil. The phase identification process involves calculating the most likely match score for a given phase based on peak intensity and peak position. The weight fraction is calculated by comparing the intensity of the most intense peaks of that phase with standards. The Intensities of the diffraction peaks are mainly governed by the amount of material. The diffraction patterns and the peak search diagram are shown in Figures 4.3, 4.4 and 4.5 respectively. It should be clear however, that the XRD analysis is qualitative in nature and may not reflect the actual composition due to sampling.

Table 4.1: Summary of the Geotechnical Properties of Ar-Riyas Sabkha

Properties		unit	Value
Particle size range		-	More than 50% passing ASTM sieve 200
Liquid Limit (LL)	With Distilled Water	%	42.5
	With Sabkha Brine	%	33
Plastic Limit (PL)	With Distilled Water	%	26.3
	With Sabkha Brine	%	20.4
Plasticity Index (PI)	With Distilled Water	-	16.2
	With Sabkha Brine	-	12.6
AASHTO Classification		-	A-6
USCS Classification		-	CL
Maximum dry density (Modified Proctor test)		g/cm^3	1.80
Optimum moisture content (OMC)		%	14

Table 4.2: Summary of the XRD Analysis of Ar-Riyas Sabkha

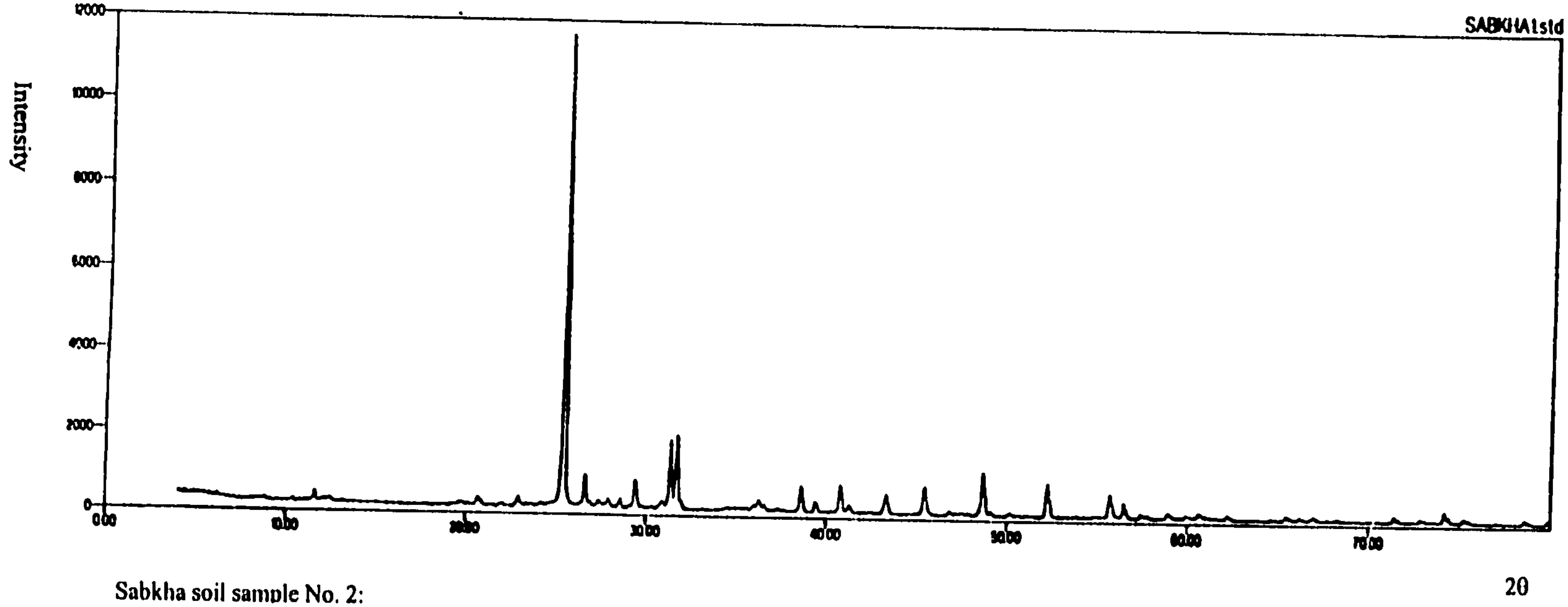
Sabkha Soil Sample 1:

Phases	Minerals	Weight %
Calcium Sulfate (Anhydrite)	$CaSO_4$	88
Halite	NaCl	5
Calcite	$CaCO_3$	5
Ankerite	$Ca(Mg_{0.67}Fe_{0.33})(CO_3)_2$	1
Quartz	SiO_2	1

Sabkha Soil Sample 2:

Phases	Minerals	Weight %
Calcium Sulfate (Anhydrite)	$CaSO_4$	81
Halite	NaCl	10
Quartz	SiO_2	5
Calcite	$CaCO_3$	2
Brushite	$CaPO_3(OH).2H_2O$	1

Sabkha soil sample No. 1:



Sabkha soil sample No. 2:

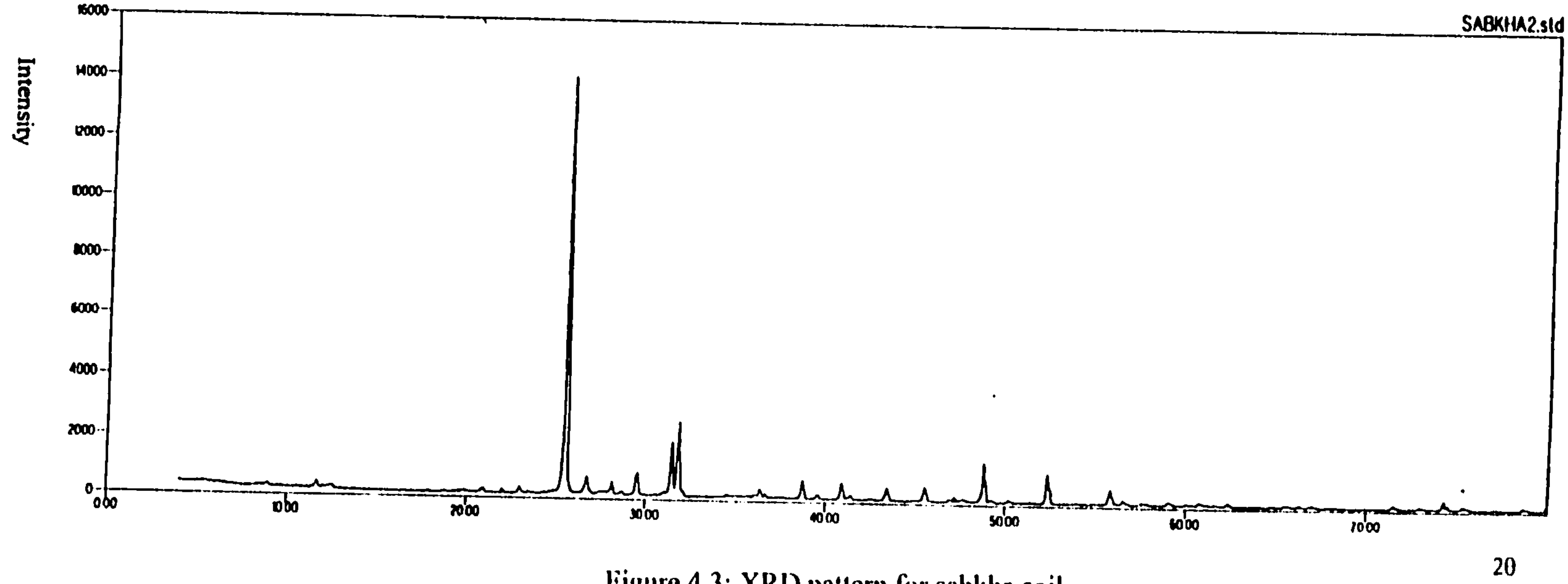


Figure 4.3: XRD pattern for sabkha soil

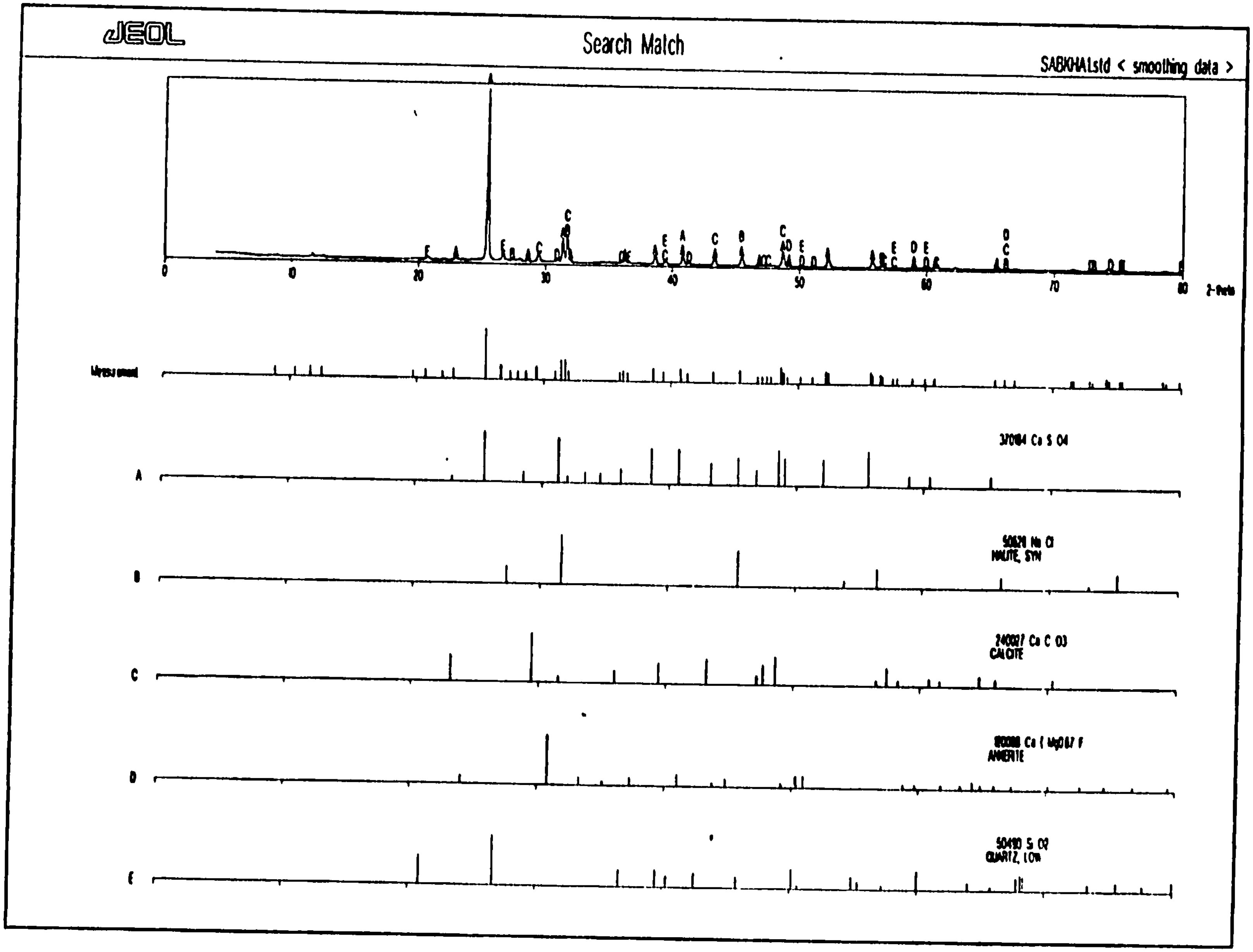


Figure 4.4: Search match for peaks of sabkha soil sample No. 1

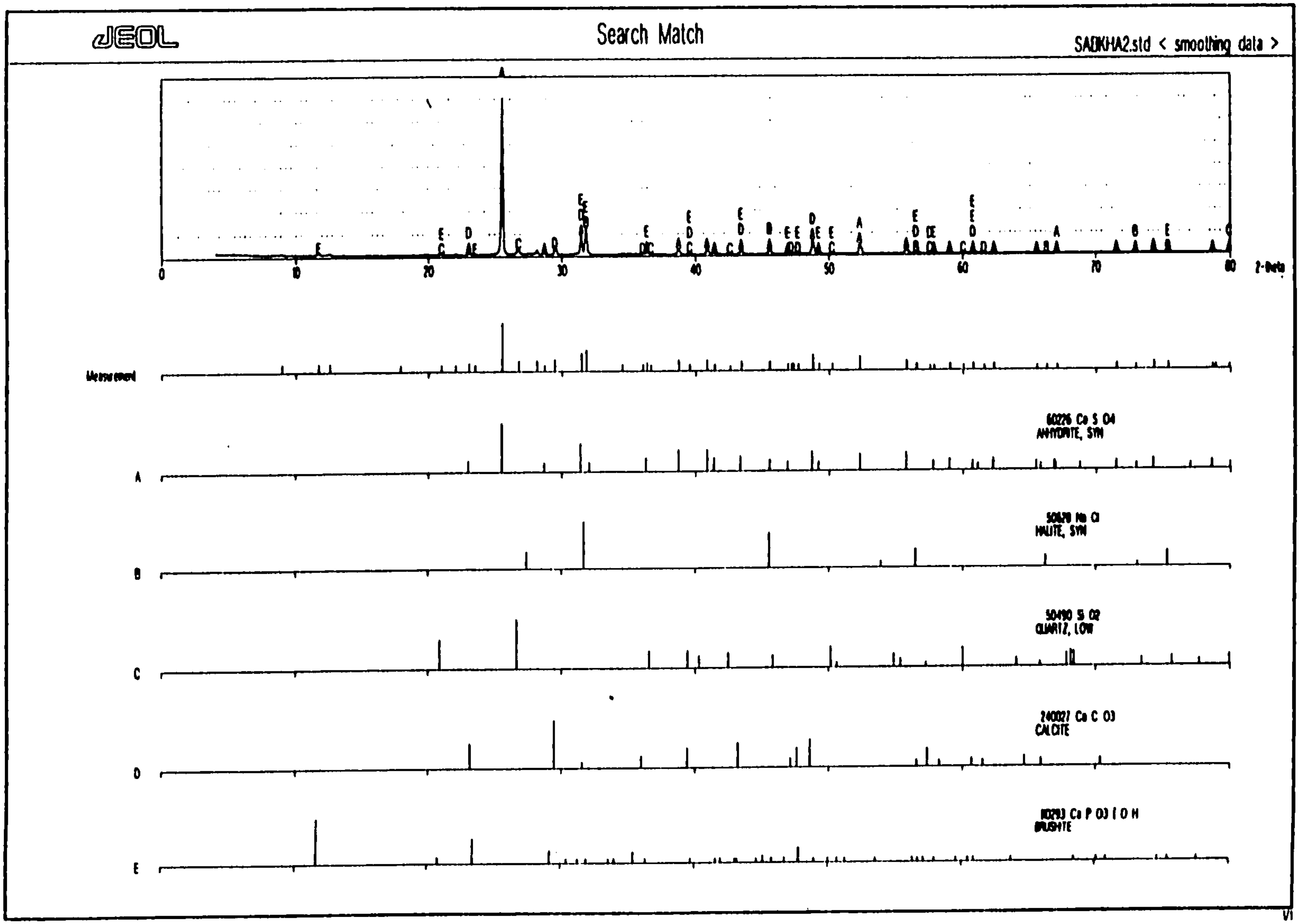


Figure 4.5: Search match for peaks of sabkha soil sample No. 2

4.2.1.4 Moisture-Density Relationship

In order to determine the moisture content-dry density (w-γ_d) relationship, modified proctor compaction test was carried out at different values of moisture content. The results of these tests are shown in Figure 4.6. The moisture content (w_{opt}) versus dry density curve shows a peak giving optimum moisture content of 14% and a maximum dry density ($\gamma_{d\ max}$) of 1.80 g/cm^3.

4.2.1.5 California Bearing Ratio (CBR) Test

The California-bearing ratio (CBR) test was conducted for all samples prepared for the compaction test (i.e. at different moisture contents) to assess the moisture sensitivity of the sabkha. Both as-molded and soaked CBR tests were performed and the variations of CBR values with the molding moisture content are shown in Figure 4.6. The as-molded test samples were tested right after the compaction while for soaked tests, samples were soaked for 96 hours prior to testing. In Figure 4.6, the curves of dry density and CBR are superimposed on the same figure. This method is very useful when dealing with the moisture sensitive soils. The CBR results indicate the acute water sensitivity of sabkha. The CBR value near the optimum moisture content on the dry side of optimum is 66% and on the wet side of optimum, it is very low and could be as low as 3%. This clearly indicates the acute water sensitivity, whereby almost a complete loss of strength resulted when compacting the material just wet of optimum.

On the other hand, the soaked CBR does not exceed the value of four, regardless of the molding moisture content. The sensitivity of sabkha to the moisture content is indicated by the significant reduction in the CBR values when the moisture content increases above the optimum moisture content. Moreover, a severe reduction in the CBR resulted from

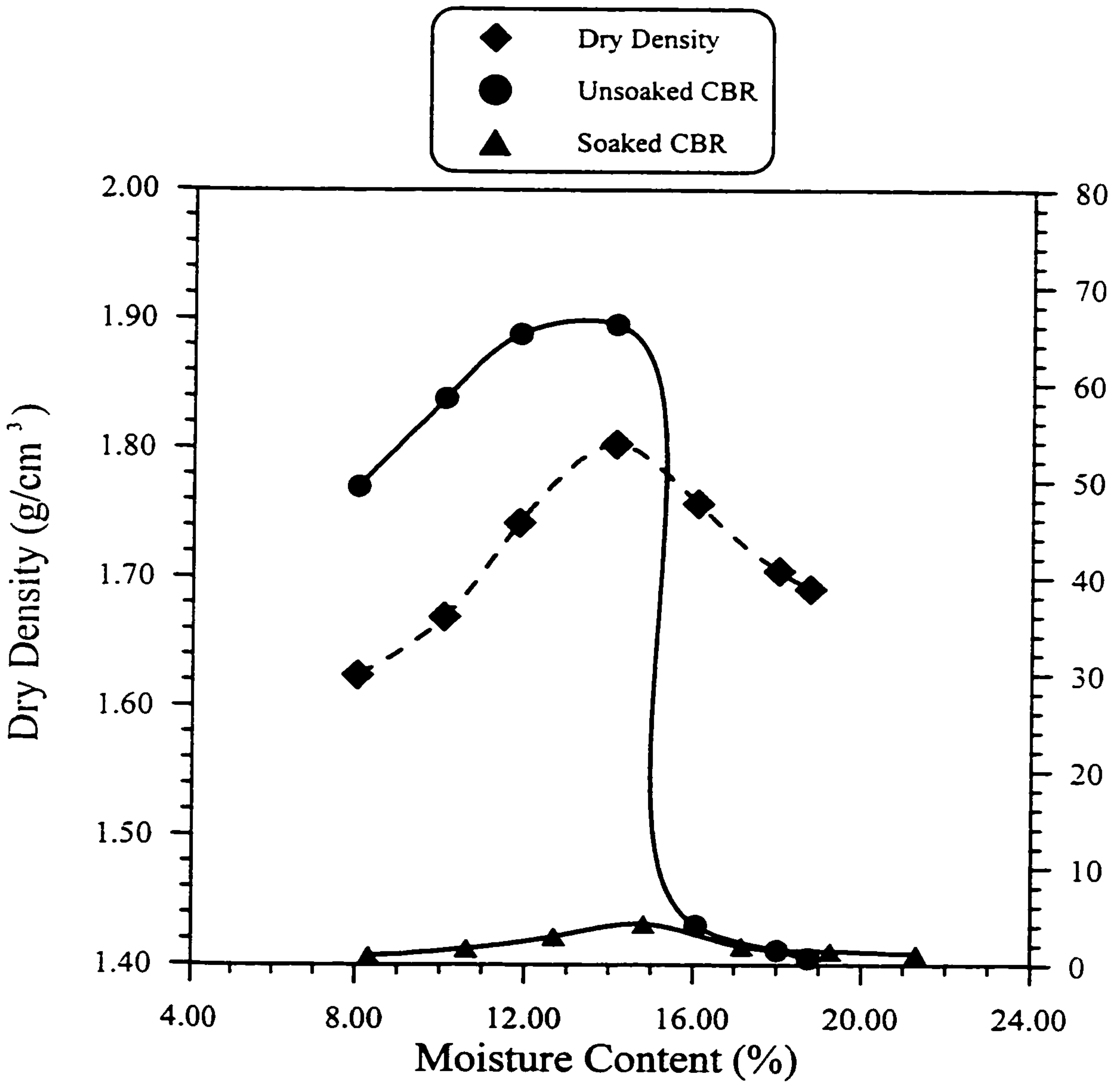


Figure 4.6 : Effect of moisture content on the dry density and CBR of sabkha soil

soaking, on both dry and wet side of optimum. In addition, the curves clearly indicate that the higher CBR values were obtained for a sample prepared at the optimum moisture content regardless of soaking.

4.2.2 Steel Slag Aggregate (SSA) Properties

In this study, SSA was used as a graded base material. Steel slag aggregate was used because of its higher density and thus strength. The high density was achieved by pluviating the slag aggregate from a height of one meter. The slag used for this study contains the fine particles ranging from 0.1 to 2 mm. Sieve analysis was performed to get the grain size distribution curve shown in Figure 4.7. The specific gravity for the slag aggregate was found to be 3.47.

4.2.3 Geotextile Properties

Three types of non-woven needle punched geotextiles were used in this study. They are A-140, A-300 and A-400. These three grades of geotextiles are from the same manufacturer. The properties of these geotextiles are tabulated in Table 4.3. It is clearly seen that three geotextiles have distinct variations in their thickness, strength and mass per unit area. However, their elongation is almost the same. In addition the elongation is relatively high compared to other available geotextiles. Geotextiles with high elongation may not be the best for reinforcement of soft soils, however the local availability encouraged their use in this experimental program.

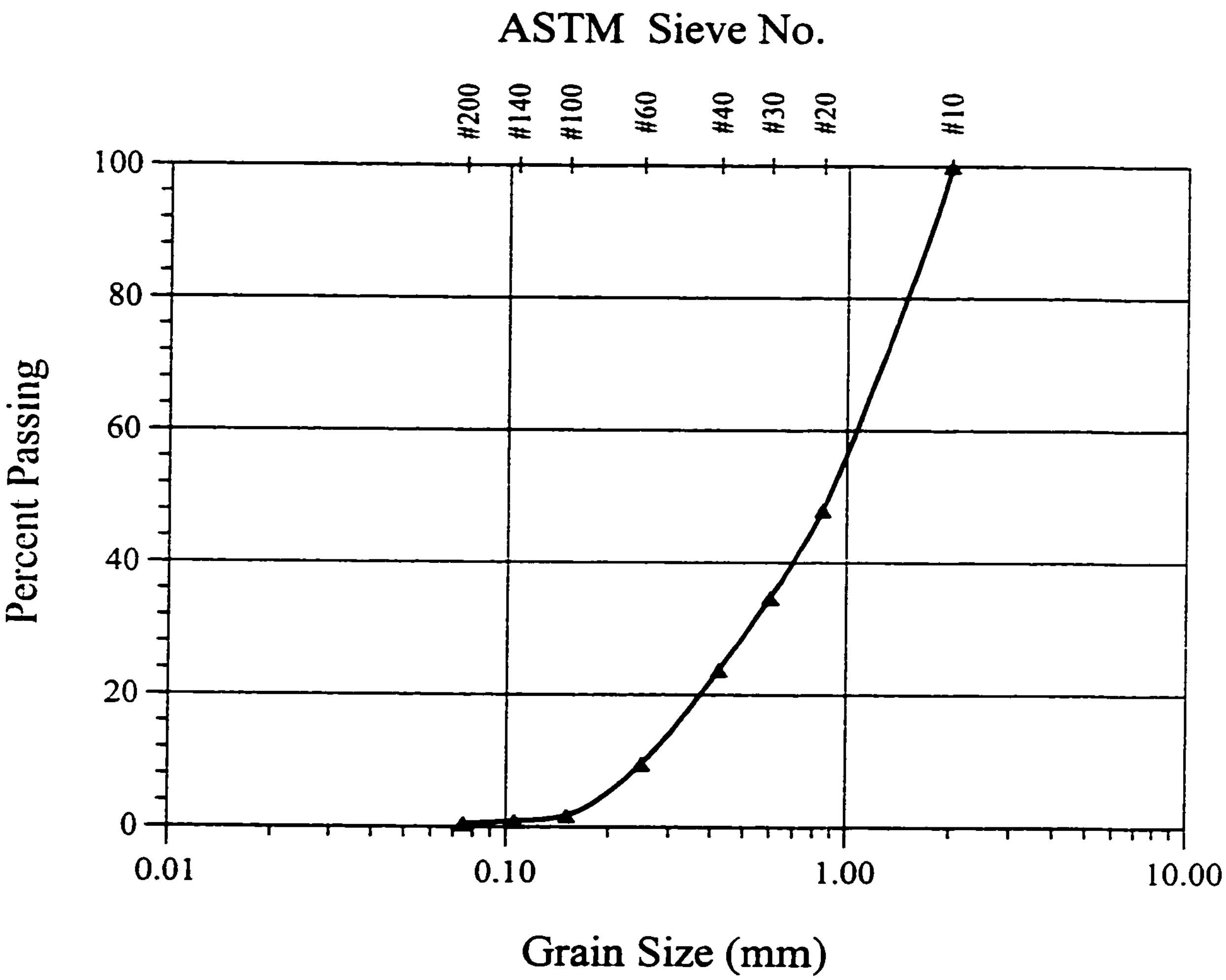


Figure 4.7: Grain size distribution curve for steel slag aggregate

Table 4.3: Summary of the Technical Specifications of the Geotextiles*

Characteristics	Standard	Units	Geotextile Type (Non Woven)		
			A-140	A-300	A-400
Mass per unit area	ASTM D5261	g/m^2	140	300	400
Thickness (under 2 kN/m^2)	ASTM D 5199	mm	2.0	3.2	4.0
Tensile strength (MD/CD)	EN 29073-3	N/5cm	350/480	900/1200	1000/1400
Elongation (MD/CD)	EN 29073-3	%	>70/>80	>70/>80	>70/>80
Grab Strength (MD/CD)	ASTM D 4632	N	380/500	350/550	1100/1500
Grab Elongation (MD/CD)	ASTM D 4632	%	>80/>90	>80/>90	>80/>90
Permeability, K	ASTM D 4491	cm/s	0.5	0.45	0.45
Transmittivity (at 2kN/m^2)	ASTM D 4716	10^{-6} x m^2/s	39	55	70
A.O.S (O95)	ASTM D 4751	micron	106	75	70

MD: Machine Direction
CD: Cross Machine Direction
* As presented by the manufacturer

4.3 Load-Carrying Capacity Results

The main objective of this study is to determine the load-carrying capacity of sabkha-aggregate and Sabkha-Fabric-Aggregate system at different conditions under static and dynamic loading. The samples used for the testing consist of two structural layers. The top layer is steel slag aggregate (SSA), which acts as a graded base layer. The bottom layer is sabkha soil and acts as a subgrade. Non-woven needle punched geotextile was placed between the Sabkha soil and slag layers in samples in which geotextiles was used as reinforcement.

4.3.1 Static Loading Results

The objective of conducting static loading was to determine the load-carrying capacity of sabkha soil samples for 30 mm deformation, for as-molded and soaked conditions and for samples with and without geotextile. In all static loading tests, base thickness was kept constant as 65mm, giving a ratio of thickness to loading plate radius of 1. The three geotextile grades were used. The permanent deformations and the corresponding static load data were recorded for all the tests. The effect of different parameters is presented in the following section.

4.3.1.1 Effect of Soaking

In order to analyze the effect of soaking on the sabkha soil, a number of tests were performed and their results are presented in Table 4.4. Figure 4.8 shows that the total load required for 30 mm deformation was 14.3 KN and 1.8 KN for as-molded and soaked samples, respectively. This behavior clearly indicates that the load-carrying capacity of sabkha soil is very low especially under soaked conditions as compared to the as-molded

Table 4.4: Summary of the Results of Static Loading

	Sample Code	Load at 30 mm Deformation	Test Condition
Without Geotextile	SG0H65W	1.8 kN	Soaked
	SG0H65D	14.3 kN	As-molded
With Geotextile	SG140H65W	2.8 kN	Soaked
	SG300H65W	6.1 kN	Soaked
	SG400H65W	6.7 kN	Soaked
	SG300H65D	23.5 kN	As-molded

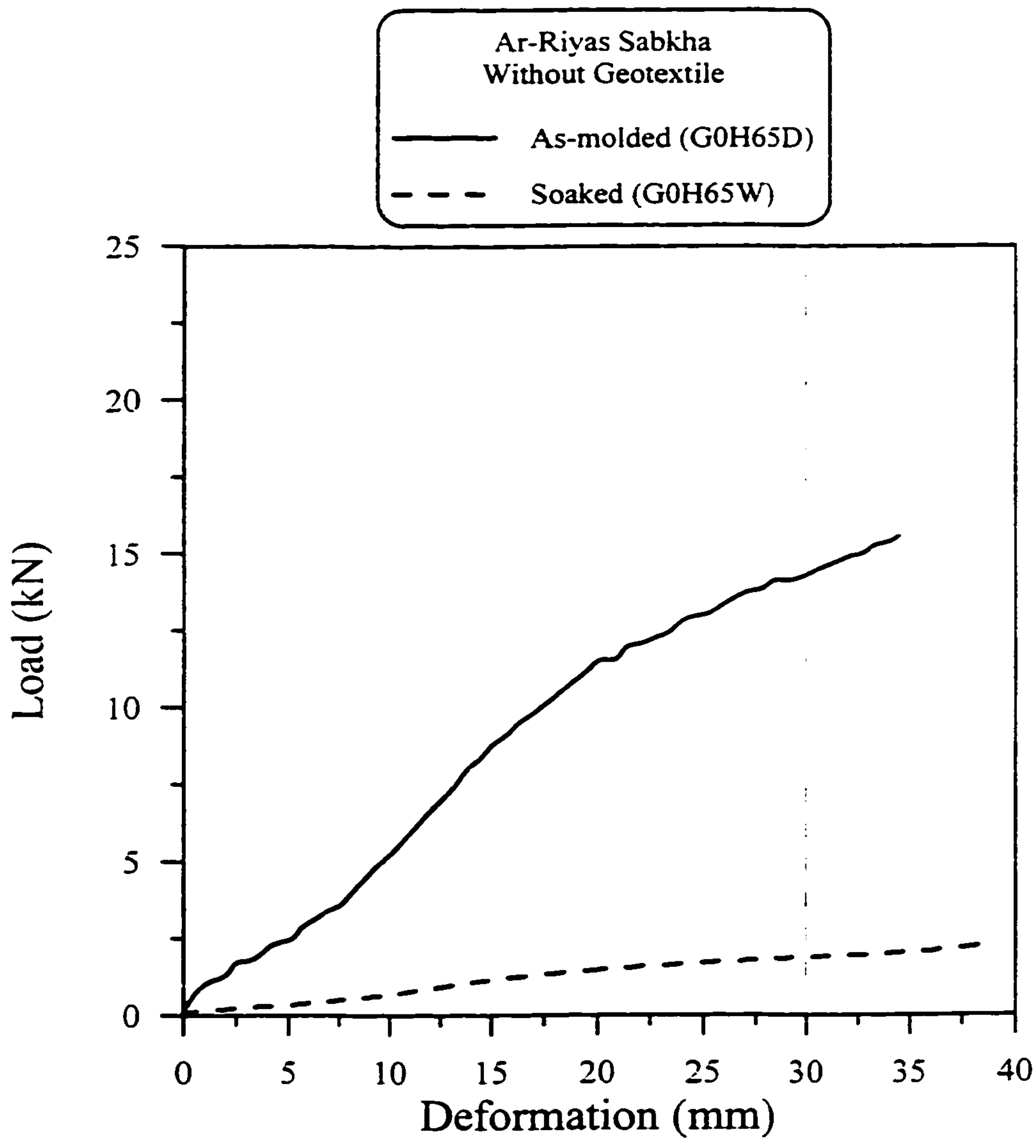


Figure 4.8: Effect of soaking on the load-carrying capacity of sabkha soil without geotextile

conditions. Such reduction (87%) is very high and will definitely have severe consequences.

Figures 4.9 and 4.10 and Table 4.4 show the result of samples tested under soaked and as-molded conditions with and without geotextile. It is clearly seen from these Figures, that the ultimate load-carrying capacity of the samples with geotextiles is much higher than those without geotextile in both as-molded and soaked conditions. In Figure 4.9, the load at 30 mm deformation of the soaked sample without geotextile is 1.8 kN, and it increased to almost 6.1 kN upon the inclusion of A-300 geotextile. Thus, there is an increase in the load-carrying capacity (LCC) and the LCC is about 3.38 times that of plain sabkha when the geotextile (A-300) was used in the system. Similar behavior is observed for the as-molded condition as shown in Figure 4.10. The load-carrying capacity of the as-molded sample for 30 mm deformation was 14.3 kN for sample without geotextile, however the values increased to 23.5 kN when the geotextile (A-300) was used. This shows that the load-carrying capacity is 1.6 times that of plain sabkha. Such results clearly show that the systems with geotextiles can carry much higher loads compared to systems without geotextiles under both as-molded and soaked conditions. Furthermore, the improvement in the load-carrying capacity of sabkha samples due to geotextile was much higher in soaked conditions compared to as-molded conditions. This is attributed to the low load-carrying capacity of soaked samples. Thus, the inclusion of geotextile will significantly improve the load-carrying capacity of the soaked sabkha. On the other hand, the as-molded samples are relatively strong and thus the induced deformation is low, and that is why the contribution of geotextile is less for as-molded samples compare to soaked ones, which are weak.

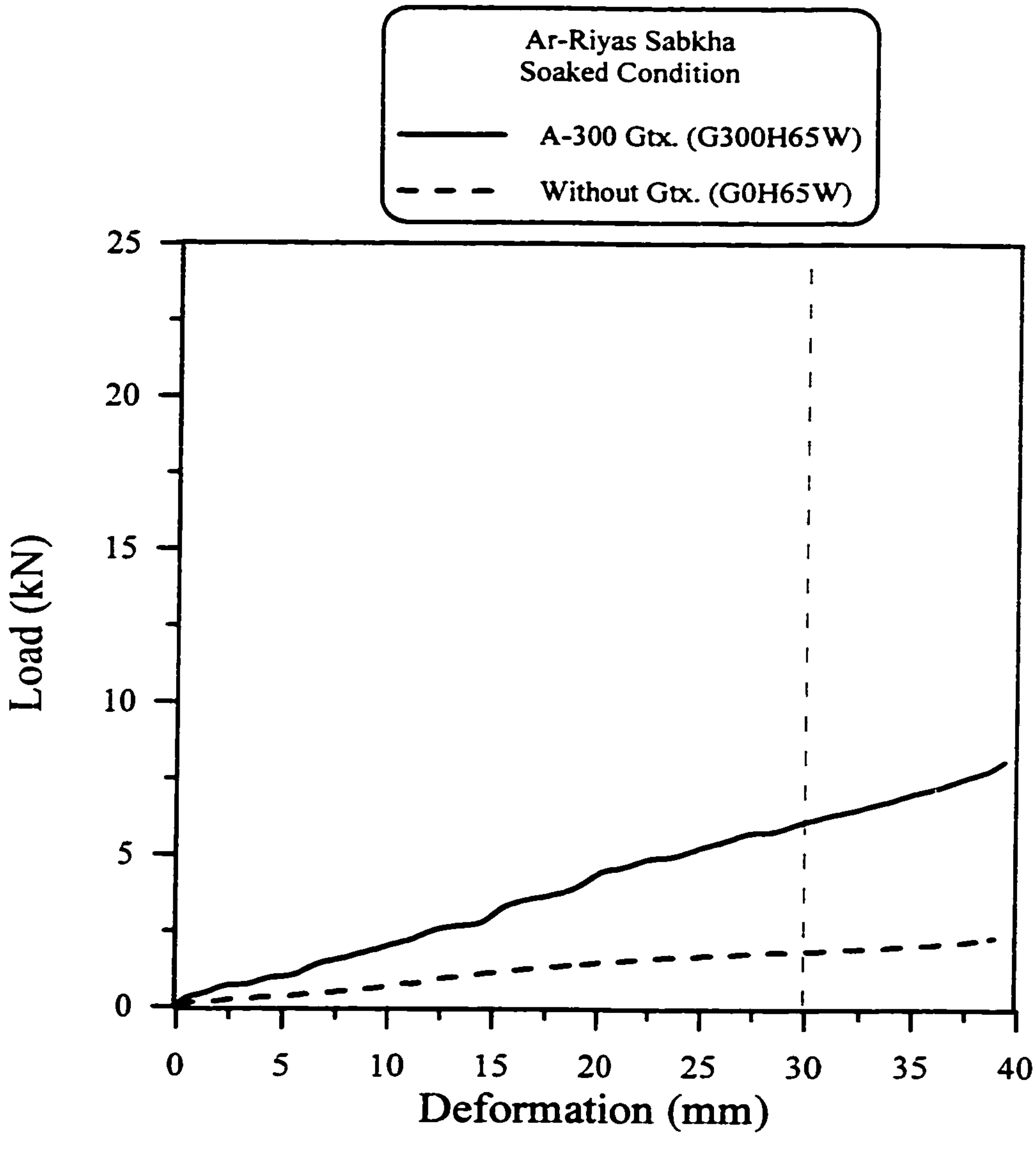


Figure 4.9: Effect of geotextile on the load-carrying capacity of sabkha soil for soaked condition

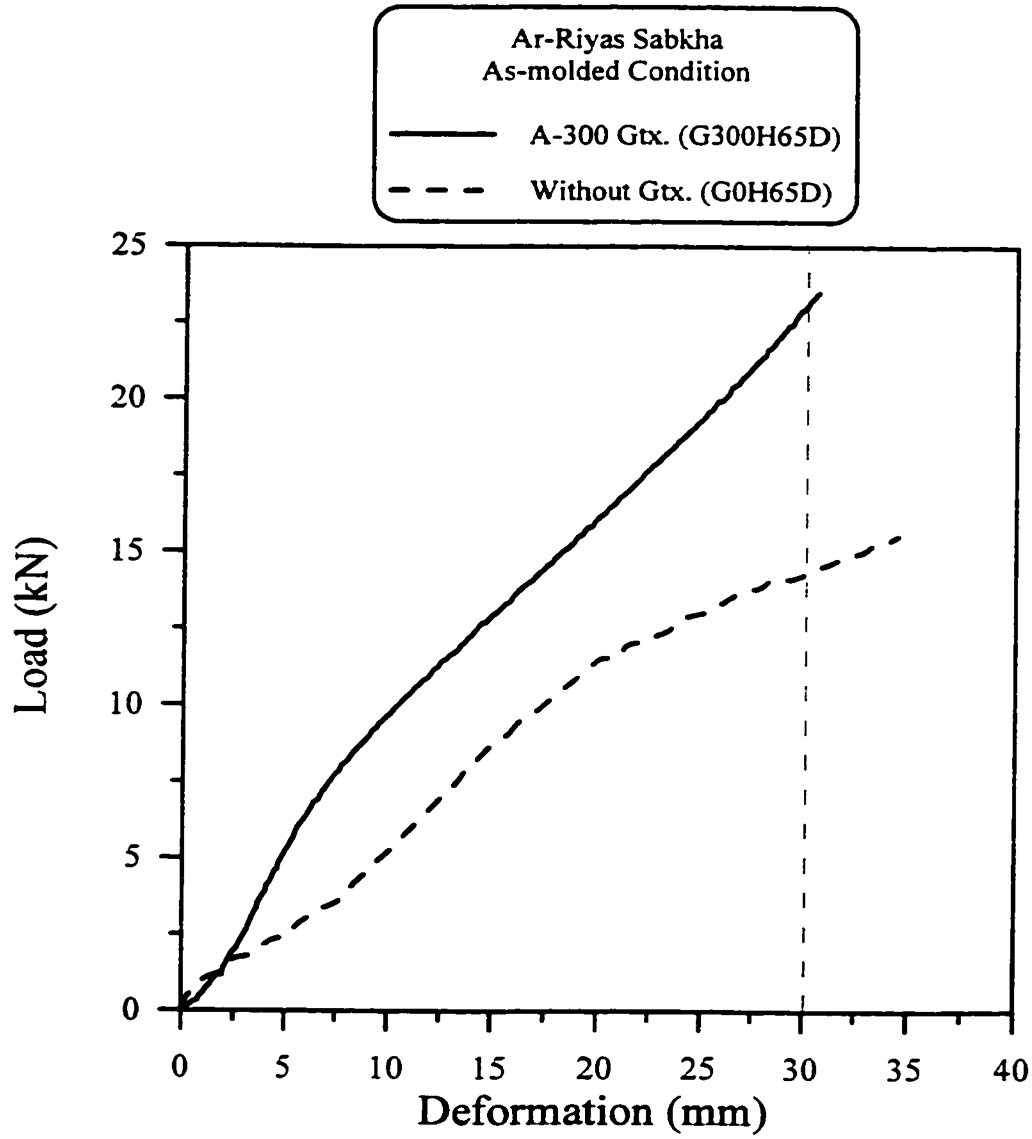


Figure 4.10: Effect of geotextile on the load-carrying capacity of sabkha soil for as-molded condition

4.3.1.2 Effect of Geotextile Grades

The effect of geotextile grade on the performance of SFA systems is another variable investigated in this study. Figure 4.11 shows the load versus deformation for a sample without geotextile and samples with three different grades of geotextile, under soaked conditions. The curves demonstrate the effect of the geotextiles grade on the improvement of the load-carrying capacity of soaked sabkha soil. The load-carrying capacity of the system without geotextile at 30 mm was 1.8 kN. However, the inclusion of A-140, A-300 and A-400 increased the values to 2.8, 6.1 and 6.7 kN, respectively. This results in an improvement of 1.56, 3.38 and 3.69 times the values of plain sabkha, respectively. It is noted that A-140 has shown little improvement in load-carrying capacity of soaked sabkha sample. However, the geotextiles A-300 and A-400 showed significant improvement. The results are summarized in Table 4.4.

In order to compare the effect of geotextile grades on the improvement of the load-carrying capacity of sabkha soil, the tensile strength of geotextiles was plotted against the load required for 30 mm deformation as shown in Figure 4.12. A simple linear relation between the load-carrying capacity of geotextile reinforced sabkha and the tensile strength of the geotextile can be used. This clearly shows that the higher the tensile strength of the geotextile the higher will be the LCC of the Sabkha-Geotextile-System. Furthermore, it clearly indicates that the tensile strength of the geotextile is a significant parameter in the selection of an effective improvement system.

The above results of the static load tests clearly show that the sabkha soil systems with geotextiles can carry much higher loads than systems without geotextile under both as-molded and soaked conditions. Furthermore, the effect of geotextile is more

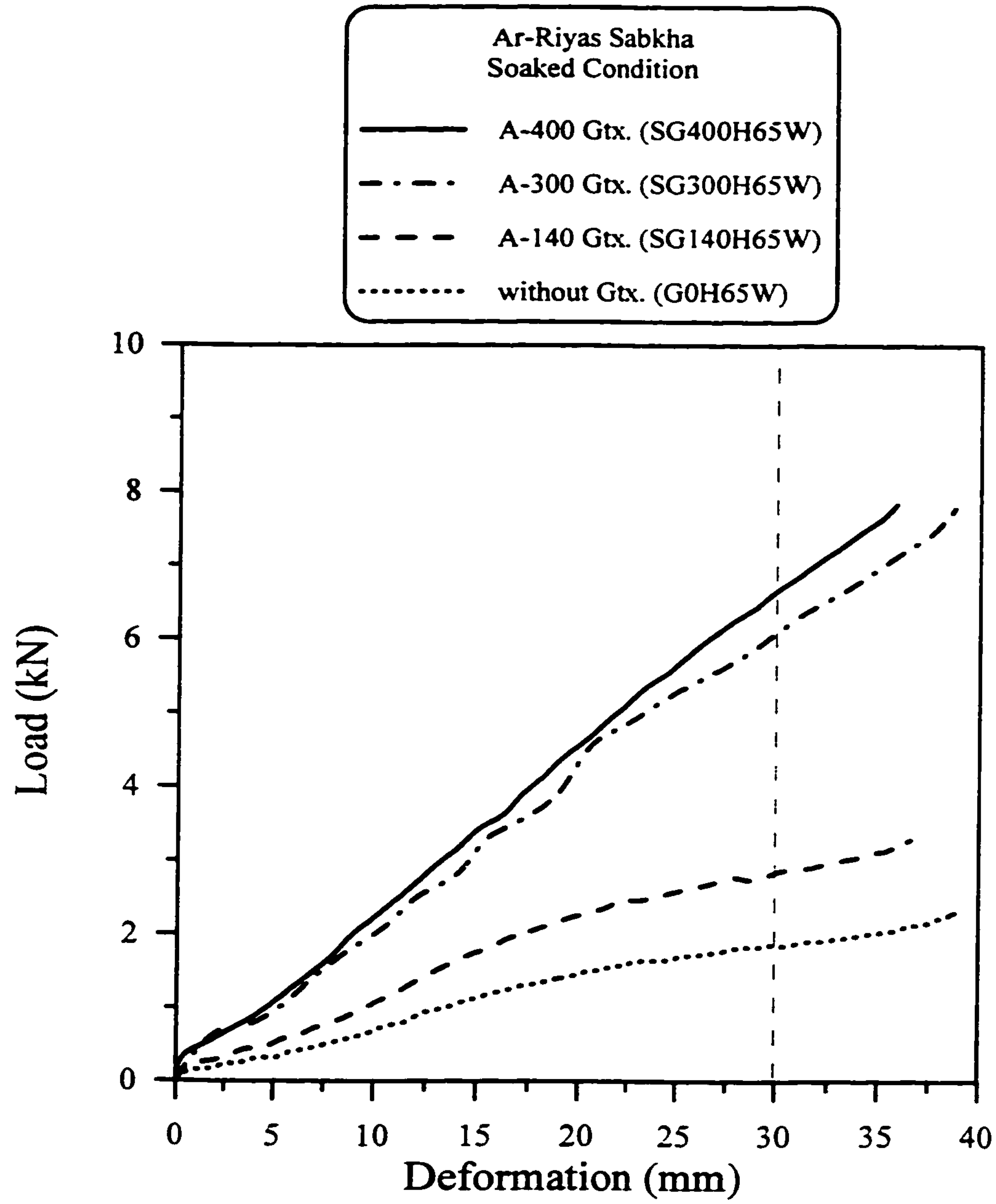


Figure 4.11: Effect of geotextile grades on the load-carrying capacity of sabkha soil for soaked condition

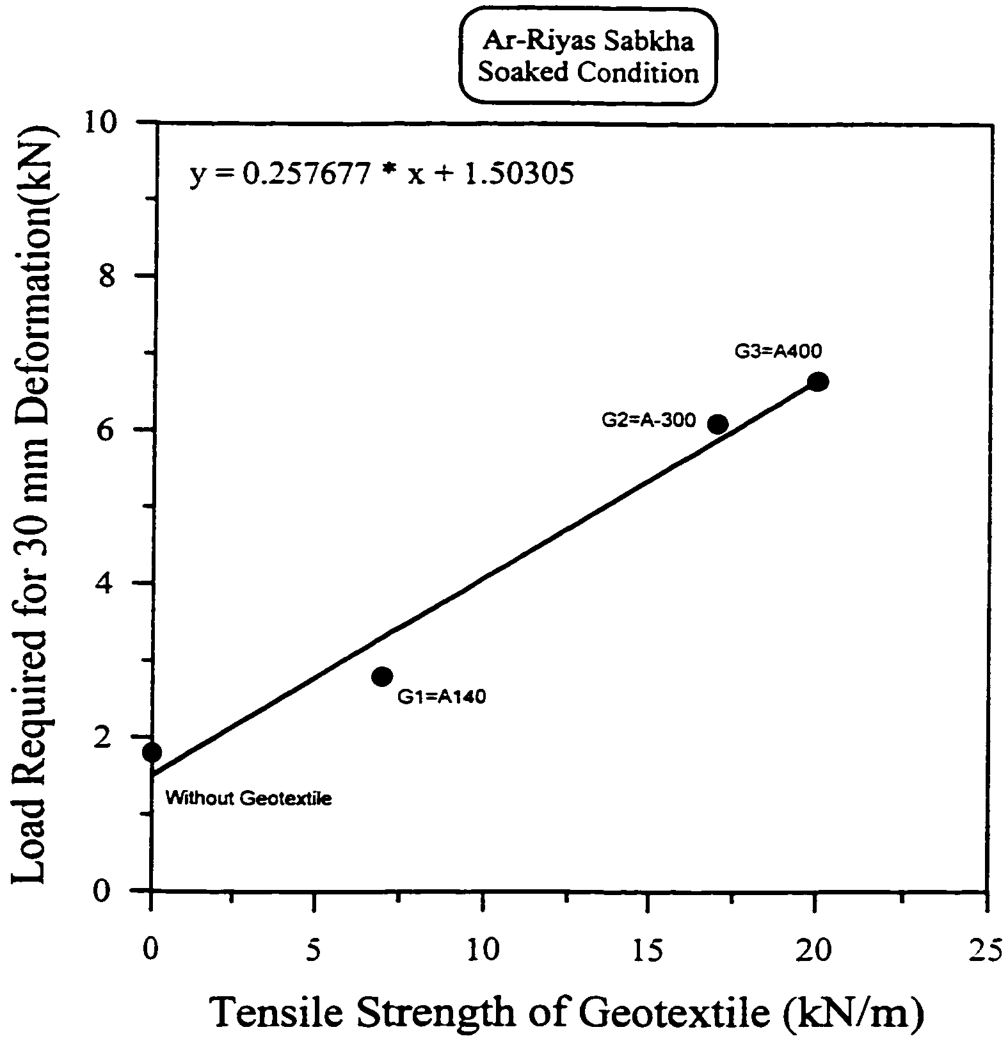


Figure 4.12: The effect of tensile strength of geotextile on the load carrying capacity of sabkha-geotextile-aggregate system

pronounced for soaked condition compared to the as-molded conditions and the amount of improvement is directly related to the tensile strength of the geotextile.

4.3.1.3 Effect of Cement Addition

Three sabkha samples having cement content of 5, 7 and 10% were prepared in order to determine the effect of cement content on the load-carrying capacity of sabkha under soaked condition. The load versus deformation curves for these tests are shown in Figure 4.13 and the results are summarized in Table 4.5. The results show that for sample with 10% cement, the load required for 30 mm deformation is about 8 kN, which is 4.4 times, the load (1.8 kN) required for the same deformation for sabkha samples without any treatment. This load is also 1.2 times the load of 6.7 kN sustained by sabkha sample reinforced with A-400 geotextile. Similarly, addition of 7% cement resulted in a load of 7.2 kN at 30 mm deformation. Such value is comparable to that obtained by adding 10% cement. However, the sample with 5% cement sustained a load 5.3 kN at 30 mm deformation. Such load is only 3 times the load carried by sabkha without improvement. These results show that the use of A-400 geotextile is more efficient than the improvement using up to 5% cement in soaked condition. Although 7% and 10% cement addition improved the load-carrying capacity. However, this improvement is not very significant when compared to that of the A-400 geotextile.

One of the major consequences of cement stabilization of sabkha soil is the long-term effect of chemical reaction between cement and sabkha salts. This requires the consideration of the environmental condition. The presence of significant amount of digenetic minerals, such as halite, gypsum, calcite, etc., in the sabkha system may significantly alter the response of sabkha to chemical stabilization (Al-Amoudi, 1994a).

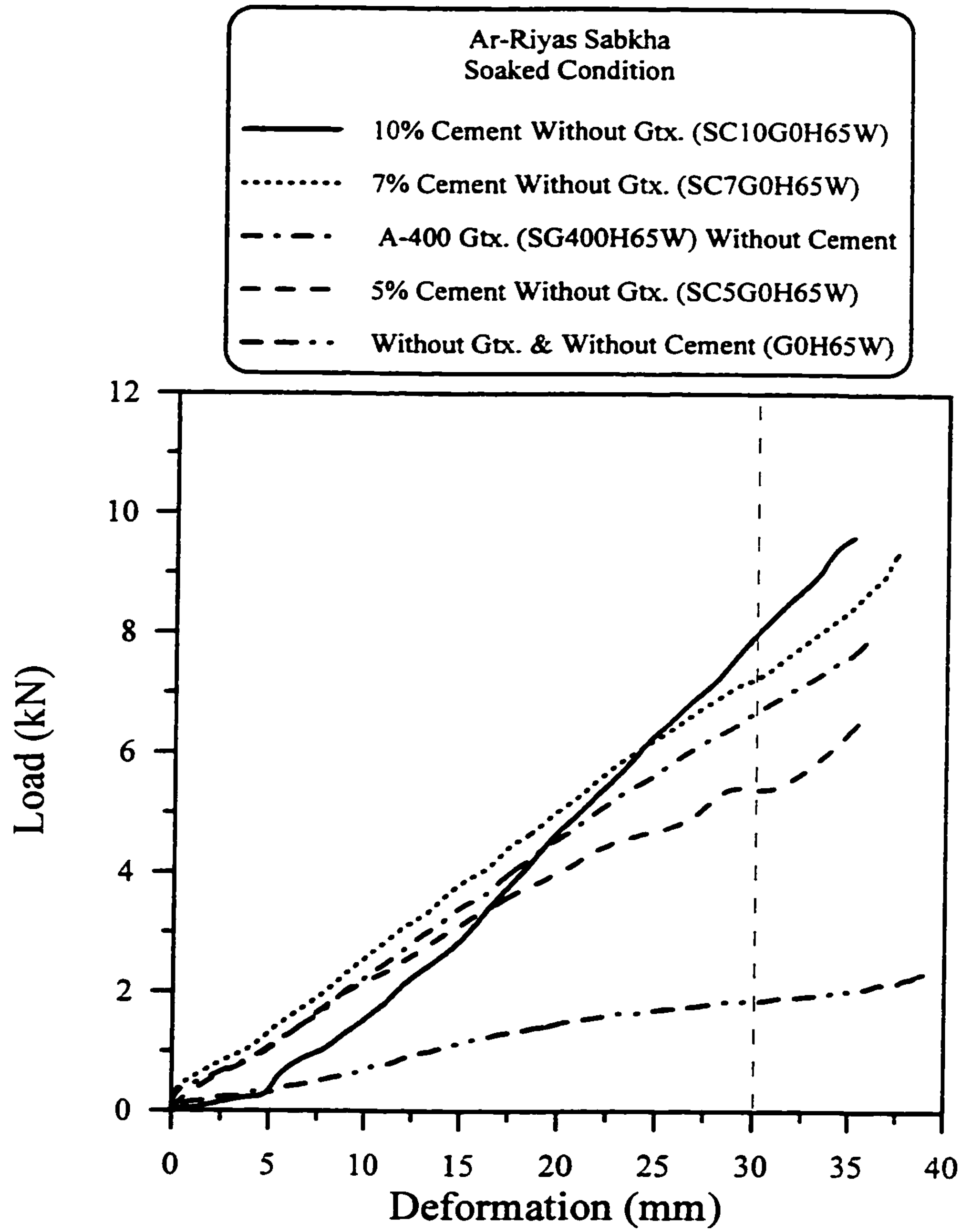


Figure 4.13: Effect of cement addition and geotextile on the load-carrying capacity of sabkha soil

Table 4.5: Summary of the Results for Different Cement Additions and Geotextiles

Sample Code	Load at 30 mm Deformation	Remarks
SG0H65W	1.8 kN	Without Gtx./ Without Cement
SG400H65W	6.7 kN	With A-400 Gtx.
SC5G0H65W	5.3 kN	With 5% Cement
SC7G0H65W	7.2 kN	With 7% Cement
SC10G0H65W	8.00 kN	With 10% Cement

In addition, the problem is significantly intensified by the co-existence of intermittent, but regularly occurring, moisture with this high salt content that is liable to produce the worst conditions and the most severe deterioration (Al-Amoudi, 1995a). The various forms of brine attack present severe conditions for ordinary Portland cement and warrants strict precautionary measures. Moreover, the conjoint presence of these salts poses several unresolved questions regarding their concomitant interaction with cement (Al-Amoudi, 1992).

4.3.1.4 Effect of Lateral Extent of Geotextile

Five tests were performed to evaluate the effect of the lateral extent of the geotextile under the loaded area. All aspects of the test (base thickness 65 mm and geotextile A-400) were kept constant except for the diameter of the geotextile. The sizes for geotextile diameter were selected to have a relation with the diameter of the loading plate (d_p=130 mm), in the ratio of 2d_p (260 mm), 3d_p (390 mm), 4d_p (520 mm) and 5.8d_p, which is equal to full diameter (750 mm) of mold as shown in Figure 4.14. The result of these tests is presented in Figure 4.15 and Table 4.6.

The comparison of two test results one without Geotextile and one with 260 mm geotextile diameter shows that the results of these two tests are almost identical and the relatively small geotextile diameter did not improve the load-carrying capacity significantly. However, geotextile diameter of 390 and 520 mm improved the load-carrying capacity to 2.7 and 3.9 kN, respectively. These test results show that the larger geotextile diameter area is more beneficial than the smaller due to the larger load distribution area. The relation between the geotextile diameter and the load is presented in Figure 4.16.

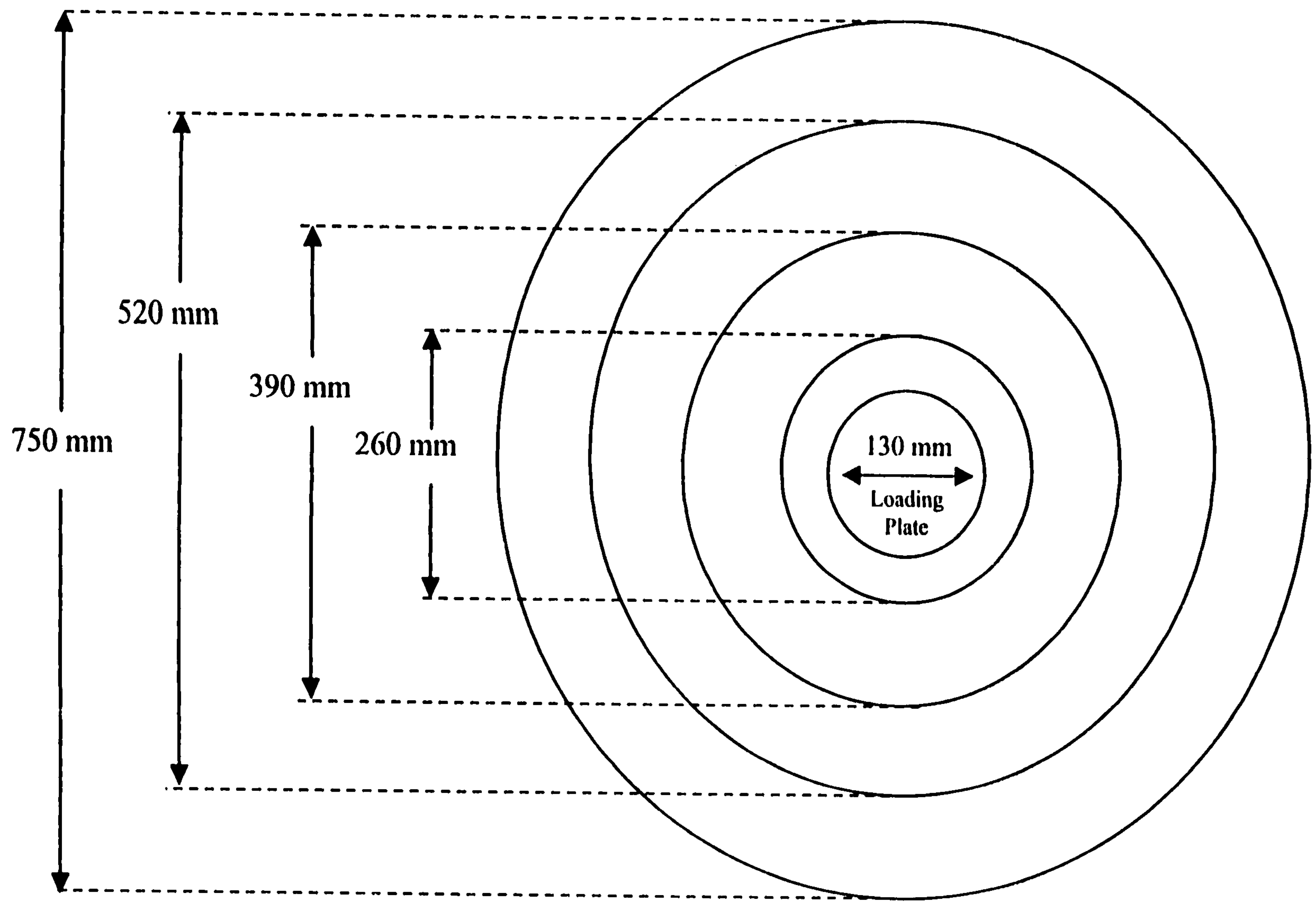


Figure 4.14: Comparison of the loading plate with the various geotextile diameters

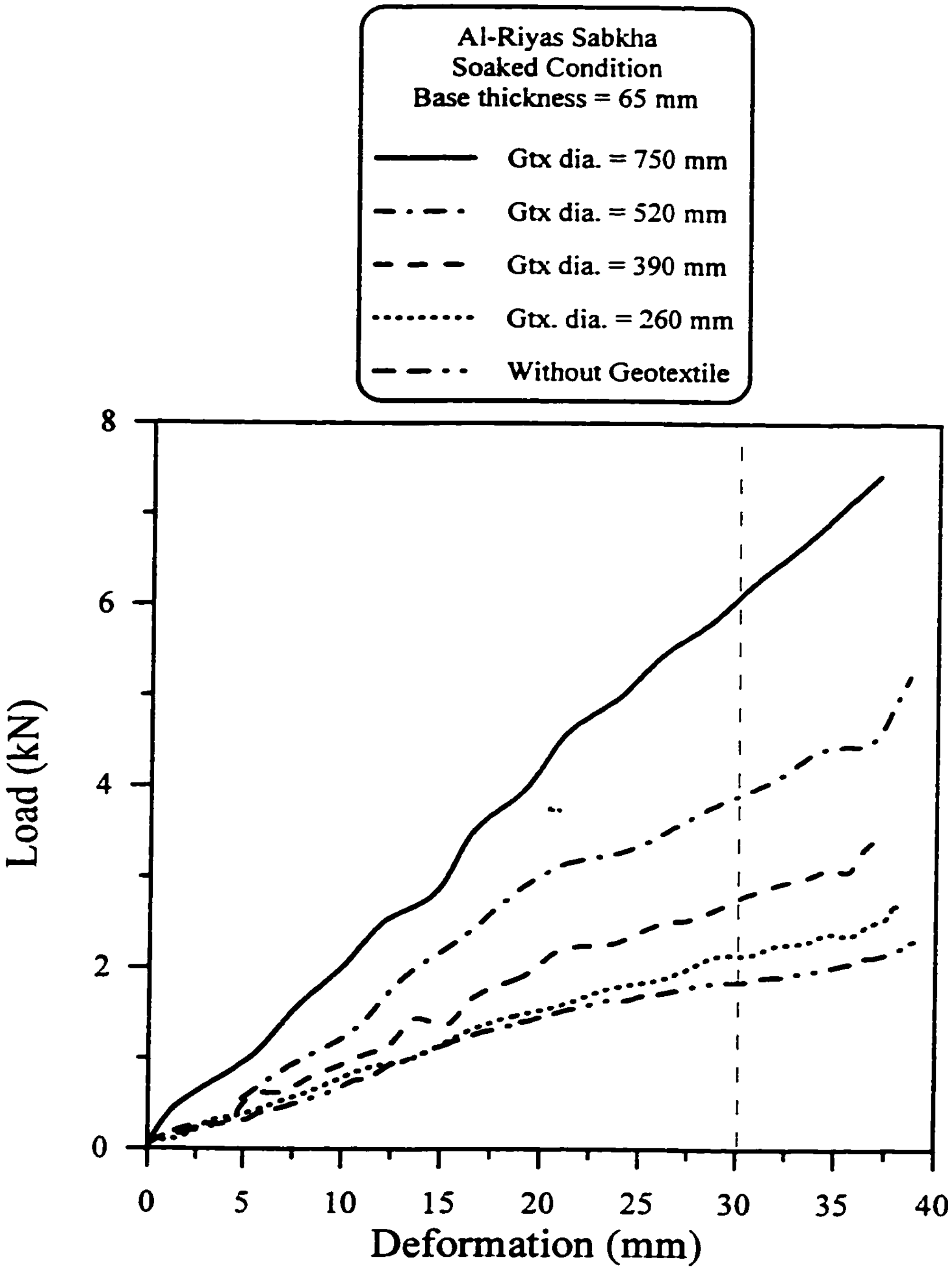


Figure 4.15: Effect of geotextile diameter on the load-carrying capacity of sabkha soil for soaked condition

Table 4.6: Summary of the Results on the Effect of Geotextile Diameter

Geotextile Diameter	Ratio of Gtx. Diameter to Loading Plate Diameter	Load at 30 mm Deformation	Load Carrying Capacity Compared to Sample Without Gtx.
Without Gtx.	—	1.8 kN	—
260 mm	2	2.1 kN	116%
390 mm	3	2.7 kN	150%
520 mm	4	3.9 kN	216%
750 mm (Full diameter)	5.8	6.7 kN	372%

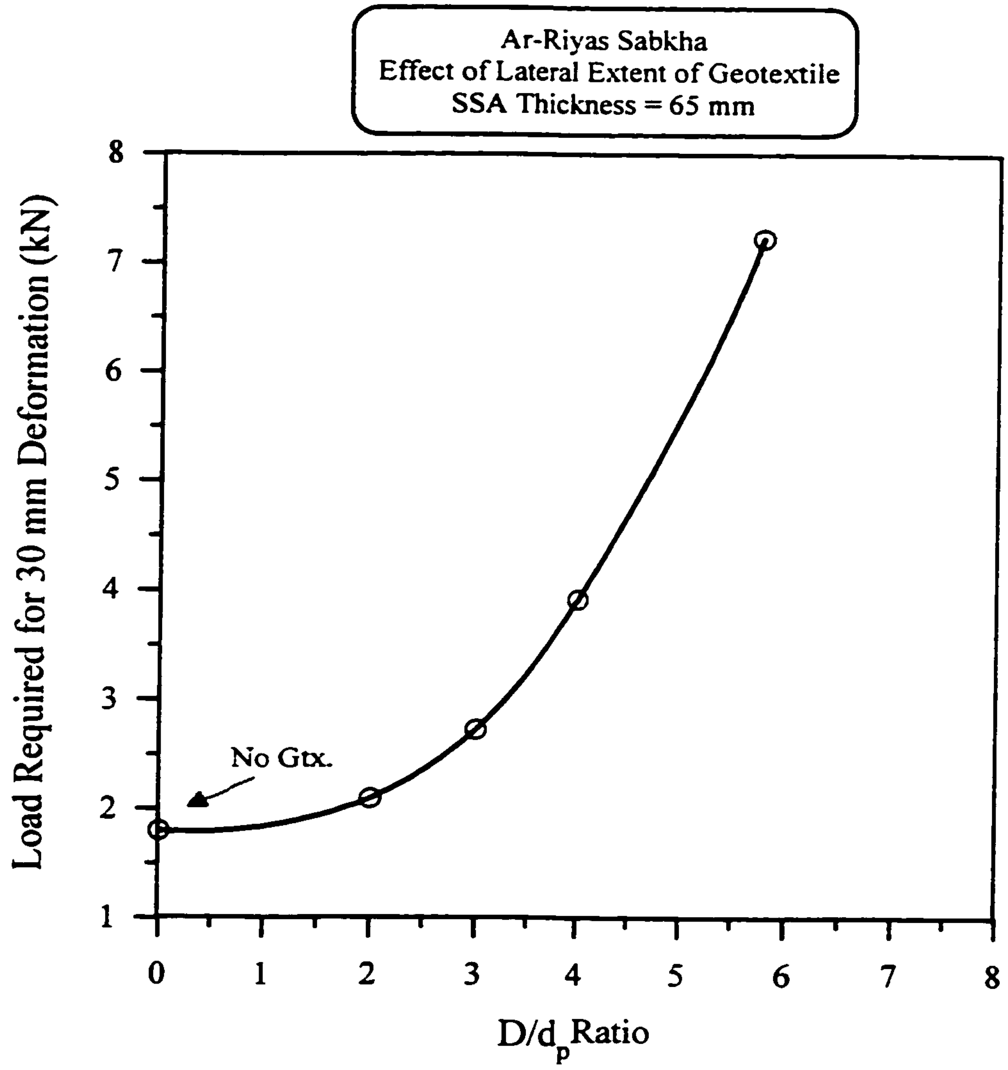


Figure 4.16: Ratio of geotextile dia. to laoding plate dia. (D/d_p) versus load required for 30 mm deformation

4.3.2 Dynamic Loading Results

In the dynamic load testing, samples were tested under three different deviatoric (pulse) stress levels. These tests were performed taking into account different parameters, which includes moisture condition, geotextile type and base thickness. Permanent deformation was the main output monitored for the dynamic load testing. It was monitored as a function of load repetitions. In some cases, the number of load repetitions required for 30 mm deformation was used for comparison. The effects of different parameters are discussed in the following paragraph.

4.3.2.1 Effect of Soaking

Soaking of sabkha soil is considered the most critical condition. Therefore, it is very important to study the behavior of sabkha subgrades under soaked conditions, with and without the inclusion of geotextiles.

The effect of sabkha soaking and the presence of a geotextile layer are shown in Figures 4.17 and 4.18. In these Figures, the total average deformation is plotted against the number of load repetitions (N). All samples were tested under a seating pressure of 10 kPa and the deviatoric (Pulse) stress of 100 kPa. The permanent deformations at selected number of load repetitions are summarized in Table 4.7.

The results in Figure 4.17 indicate that for samples without geotextiles, the permanent deformation for soaked samples is much higher than that measured for the as-molded samples at the same number of load repetitions. It can be seen clearly in Table 4.7 that the permanent deformation, at 10000 load repetitions, in the soaked sample exceeds 35 mm while in the as-molded sample it is only 14.3 mm. Similarly for the 100

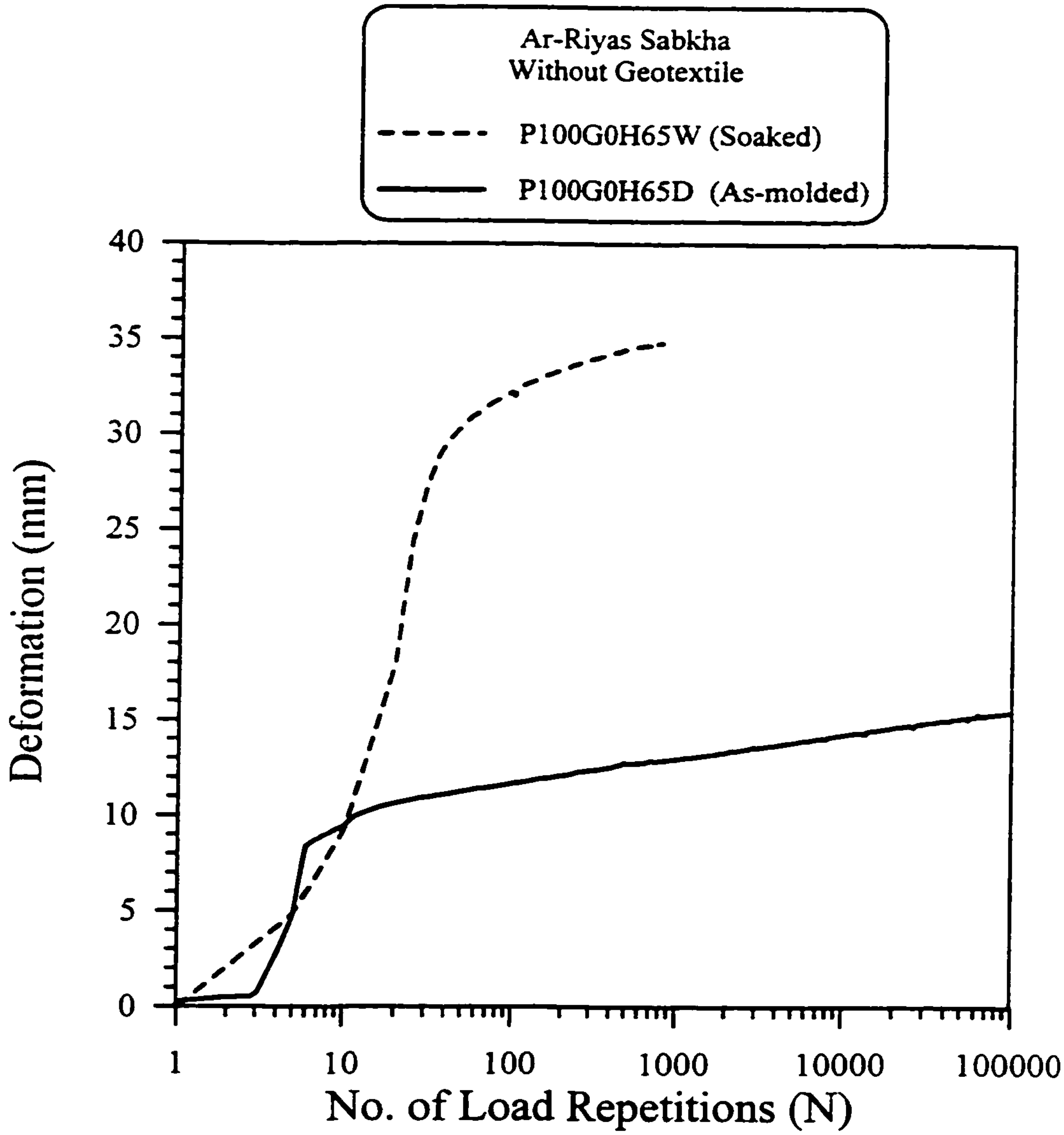


Figure 4.17: Effect of soaking on the performance of sabkha soil (without geotextile)

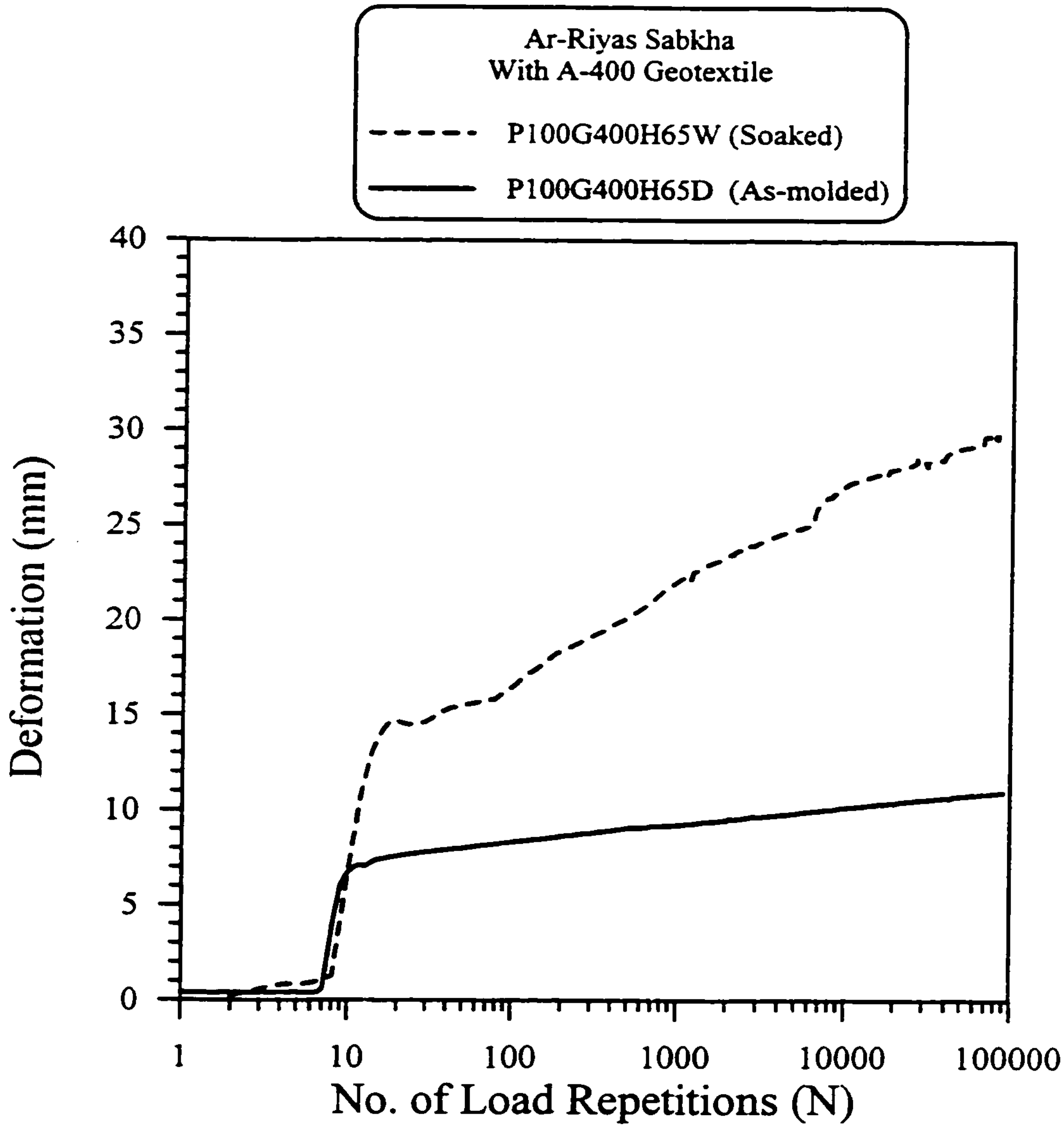


Figure 4.18: Effect of soaking on the performance of sabkha soil improved with A-400 geotextile

Table 4.7: Summary of the dynamic testing results considering the effect of soaking and inclusion of geotextile

	Deformation (mm)					
Sample Code \ No. of Load Repetitions	50	100	200	500	1000	10000
P100G0H65W (Soaked without Gtx.)	30.5	32.0	33.4	34.5	35.0	>35
P100G0H65D (As-molded without Gtx.)	11.3	11.7	12.1	12.7	13.0	14.3
P100G400H65W (Soaked with Gtx.)	15.5	16.5	18.4	20.2	22.1	27.1
P100G400H65D (As-molded with Gtx.)	8.0	8.3	8.6	9.0	9.2	10.1

load repetitions, the permanent deformation is 32 mm for the soaked sample while in the as-molded sample it is only 11.7 mm.

Similar behavior was observed in samples with geotextile as shown in Figure 4.18. The permanent deformation in the as-molded sample is only 10 mm after 10000 load repetitions while in the soaked sample it reached 24.8 mm after the same number of load repetitions. These results illustrate the unsatisfactory behavior of sabkha when becoming wet. The results also indicate that the deformation of the as-molded samples is very low compared to that of the soaked samples. Furthermore, the deformation of the as-molded samples seems to increase very slowly with the increase in N.

This is attributed to the high salt content and the presence of water sensitive ingredients such as Anhydrite. Table 4.2 shows that sabkha contains a large amount of salts in the form of calcium sulfate ($CaSO_4$) and halite (NaCl) in addition to some calcite ($CaCO_3$). These minerals act as cementing agents at low moisture contents and result in higher strength of the sabkha. This provides a hard base under normal dry conditions. However upon wetting, such cementing effects are lost, some got dissolved in water, and thus the sabkha soils loose the strength and become soft and very weak subgrade.

4.3.2.2 Effect of Base Thickness

The thickness of the base layer is one of the variables investigated in this study to quantify the effects of different base thicknesses on the performance of sabkha with and without geotextiles. In this investigation, the steel slag aggregate (SSA) base thickness was varied while other parameters were maintained the same. Three base thicknesses were tried 33 mm, 65 mm and 98 mm. Such thicknesses are related to the radius of the loading plate (65 mm), so the three thicknesses have a thickness to plate radius ratio of 1/2, 1 and 3/2 respectively.

Identical samples with and without geotextiles for the three thicknesses were tested under both as-molded and soaked conditions. Samples were tested under a seating pressure of 10 kPa, and a deviatoric (pulse) stress of 100 kPa and using A-400 geotextile (when geotextile is used). The results of the different base thicknesses for samples with and without geotextile are shown in Figure 4.19. Table 4.8 shows the deformation values at selected number of load repetitions.

These results show that for samples with geotextiles, the rate of deformation decreases with the increase in SSA base thickness for the same number of load repetitions. The deformation at 10000 load repetitions for the sample of 33, 65 and 98 mm base thicknesses are 32.1, 27.1 and 20.5 mm. In case of samples without geotextiles, the deformation value at 10000 load repetitions for the sample having 33 and 65 mm base thicknesses exceeded 35 mm. However, in the sample with base thickness 98 mm, the deformation at 1000 repetitions is 28.2 mm.

It can also be observed that in samples without geotextile and 33 mm base thickness, the permanent deformation that occurred at 500 cycles is 39.3 mm. In the same identical samples, deformation was reduced to 25.2 mm when using geotextile. Such deformation is somewhat comparable to the deformation of 20.8 mm occurred in the sample with 98 mm base thickness without geotextile. Therefore, it is clearly seen that the geotextile reduces the deformation and its effect is somewhat equivalent to that when increasing base thickness by 50%.

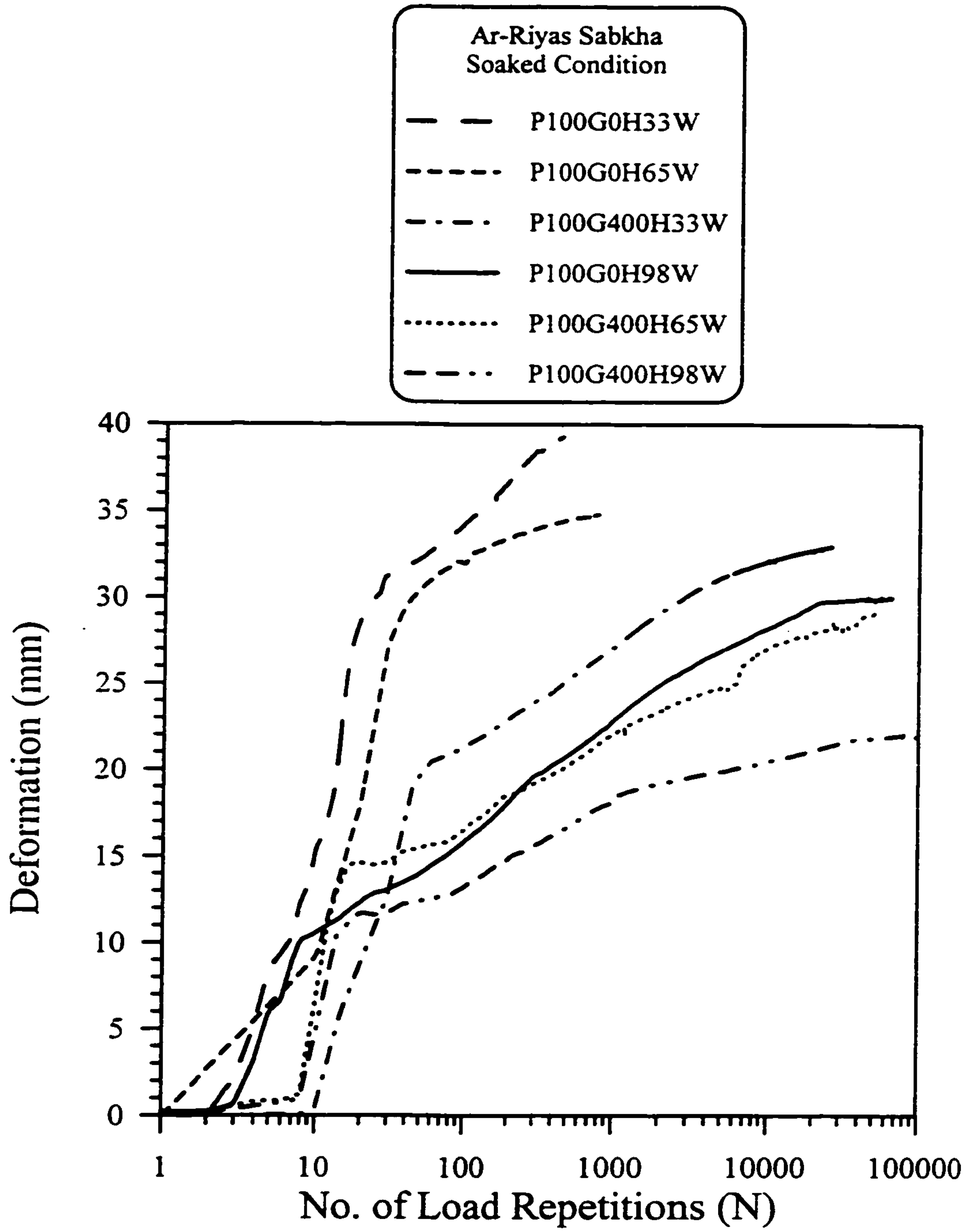


Figure 4.19: Effect of base thickness on the performance of sabkha soil (with and without geotextile) under soaked condition

Table 4.8: Summary of the dynamic testing results considering the effect of base thickness

Sample Code \ No. of Load Repetitions	Deformation (mm)					
	50	100	200	500	1000	10000
P100G0H33W (Soaked without Gtx.)	32.3	34.3	36.7	39.3	>40	>40
P100G400H33W (Soaked with Gtx.)	20.0	21.4	23.0	25.2	27.1	32.1
P100G0H65W (Soaked without Gtx.)	30.5	32.0	33.4	34.5	35.0	>35
P100G400H65W (Soaked with Gtx.)	15.5	16.5	18.4	20.2	22.1	27.1
P100G0H98W (Soaked without Gtx.)	14.0	15.8	18.1	20.8	22.8	28.2
P100G400H98W (Soaked with Gtx.)	12.4	13.3	14.8	16.6	18.1	20.5

Another observation that can be drawn from these two sets (with & without geotextile) of results is that the soaked samples without geotextiles reach the maximum deformation before reaching the steady state (constant deformation state) when base thickness is less than 98 mm. However, similar samples with geotextiles reach a constant deformation after certain N values (10000 repetitions) and this was labeled the steady state condition.

Permanent deformations at 100, 500, 1000 and 10000 load repetitions are selected for samples with and without geotextiles to enable comparison of the performance of the material with and without geotextile taking into account the base thickness. An Indicator Ratio (I.R.) is calculated by dividing the value of the permanent deformation measured in a sample without geotextile by the corresponding value of an identical sample with geotextile at the same number of load repetition (N):

$$(\text{I.R.}) = \frac{\text{Permanent Deformation at N Repetitions Without Gtx.}}{\text{Permanent Deformation at N Repetitions With Gtx.}}$$

The aim of this I.R. is to quantify the significance of the geotextiles in reducing the permanent deformations of SFA systems with different base thickness. Higher values of I.R. indicate better performance of the system. These values are summarized in Table 4.9.

The Permanent deformations versus thickness of base at different load repetition (N) are plotted in Figure 4.20 and 4.21 for samples with and without geotextiles, respectively. These Figures indicate that the permanent deformation decreases with increasing the thickness of the base. This is mainly because when base thickness increases the load spreads over larger area at the level of the sabkha, thus reducing the stress and consequently the deformation.

Table 4.9: Summary of the dynamic testing results considering the effect of base thickness for selected No. of laod repetitions

	Gtx. Grade / Base Thickness (mm)	No. of Load Repetitions											
		100			500			1000			10000		
		G_0	A-400	IR	G_0	A-400	IR	G_0	A-400	IR	G_0	A-400	IR
Deformation (mm)	H_1=33	34.3	21.4	1.6	39.3	25.2	1.6	41.0	27.1	1.5	43.0	32.1	1.3
	H_2=65	32.0	16.5	1.9	34.5	20.2	1.7	35.0	22.1	1.6	38.0	27.1	1.4
	H_3=98	15.8	13.2	1.2	20.8	16.6	1.2	22.8	18.1	1.3	28.2	20.5	1.3

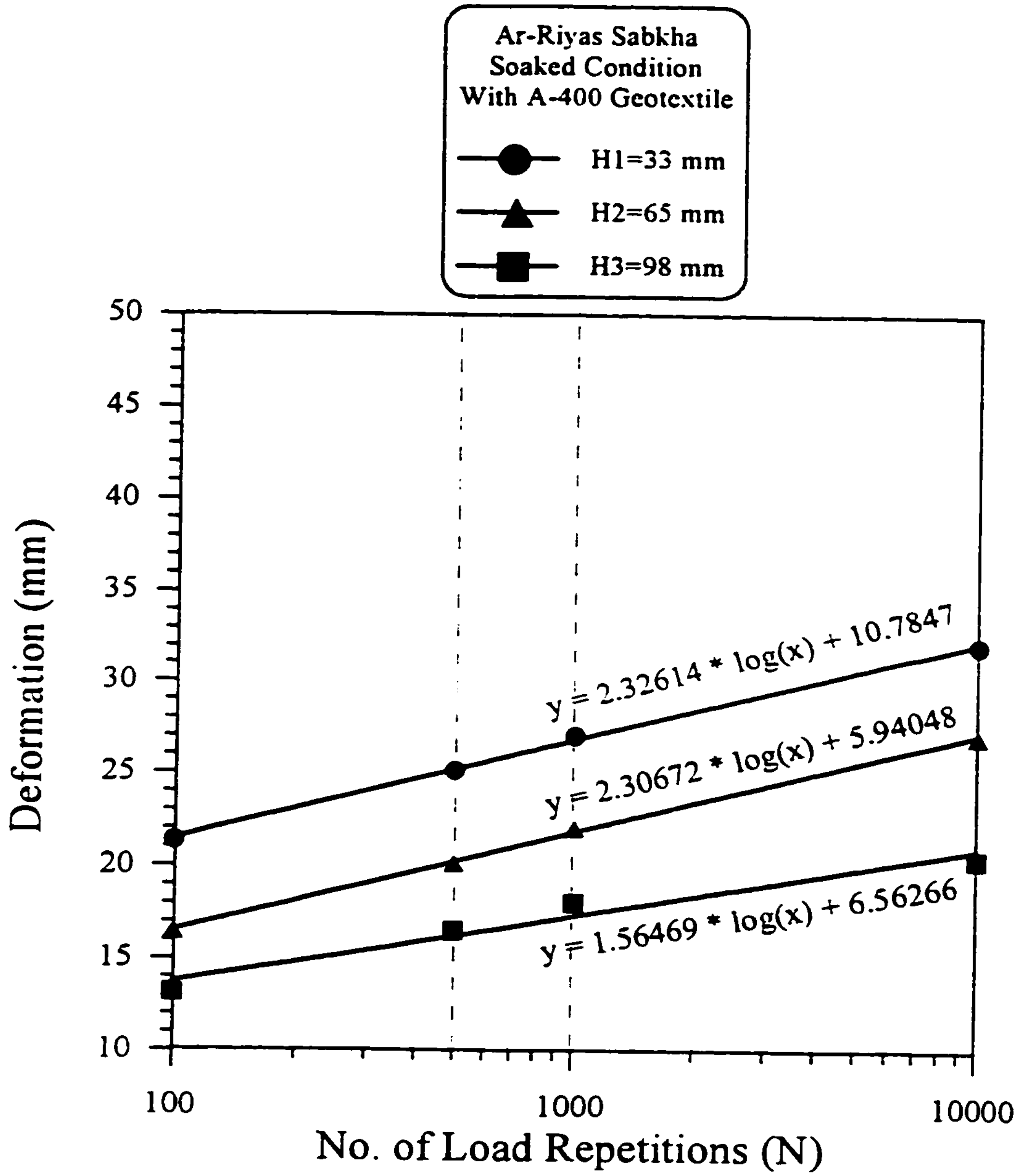


Figure 4.20: Effect of base thickness on the deformation for selected No. of load repetitions for sabkha with A-400 geotextile

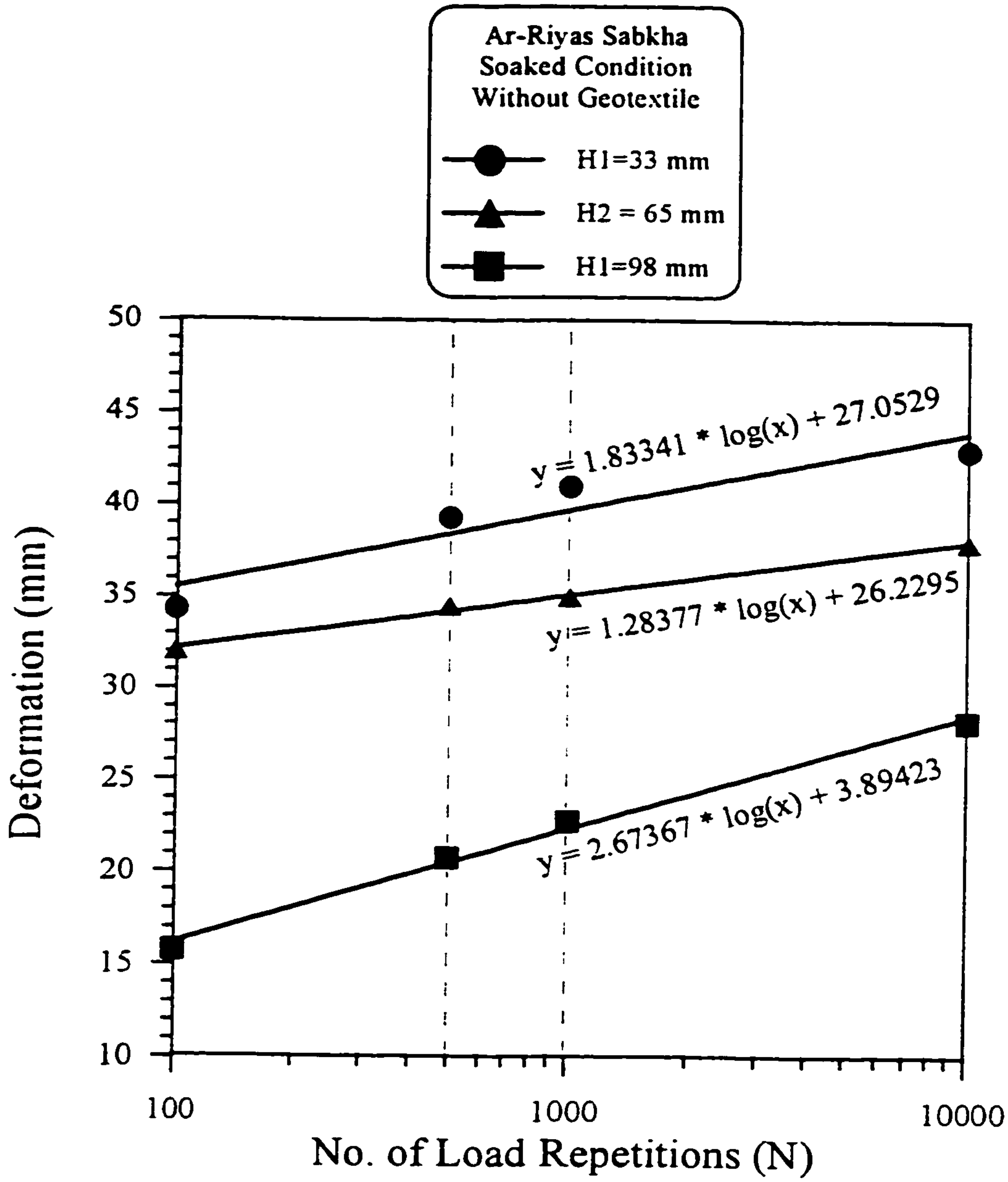


Figure 4.21: Effect of base thickness on the deformation for selected No. of load repetitions for sabkha without geotextile

Figure 4.22 shows the Indicator ratio (I.R.) versus the thickness for the selected number of load repetitions. This Figure shows that the I.R. value is increasing as the base thickness increases from 33 mm to 65 mm and it decreases as the thickness was increased to 98 mm. This means that the 33 mm base thickness is not enough to support the load and it can not provide sufficient anchorage support to hold geotextile under its weight, thereby reducing the efficiency of geotextile. As the base thickness increases to 65 mm, the reduction in the permanent deformation due to the effect of geotextile is maximum, indicating the appropriate base thickness to utilize the geotextile efficiently. The effect of geotextile becomes less when the base thickness was further increased to 98 mm, because most of the stress was taken by the thick base layer. This is reasonable since large base thickness should not be augmented by geotextile. One of the proper practices is to either increase the base thickness or to use geotextiles but not both. Similar observation can be noted in Table 4.8, where the reduction in the permanent deformation due to the use of geotextile in samples with 33 and 65 mm base thicknesses was about 36% and 41% after 500 cycles. While the reduction in the permanent deformation is only 20% for the sample with 98 mm base thickness.

4.3.2.3 Effect of Stress Levels

The effect of stress level on the performance of geotextiles in the SFA systems is another variable, which was investigated in this study. Identical samples with and without geotextiles were tested under the three different deviatoric stress levels 50 kPa, 100 kPa and 200 kPa under soaked conditions. The thickness of the base in these samples was kept 65 mm and nonwoven geotextile A-400 was used. The permanent deformation

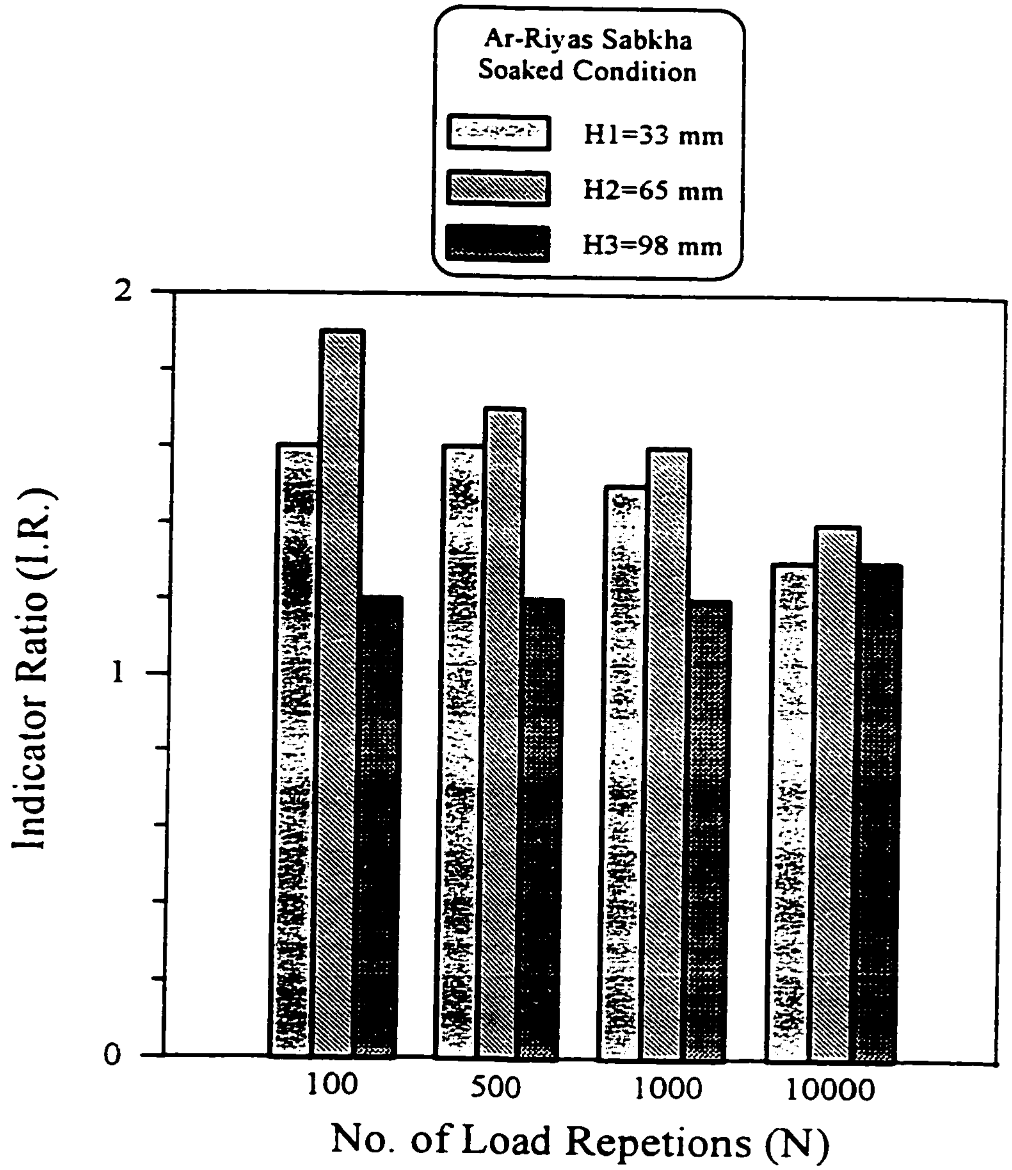


Figure 4.22: Indicator ratio versus selected No. of load repetitions for the effect of base thickness on the performance of sabkha soil

versus deviatoric (pulse) stress is plotted in Figure 4.23. Table 4.10 shows the deformation at selected number of load repetitions.

It is clearly seen from Figure 4.23 that the geotextiles decrease the permanent deformation resulted in samples, which were subjected to 50 kPa, 100 kPa stresses while there is no effect when the stress was increased to 200 kPa. The permanent deformation occurred at 1000 load repetitions, in samples without geotextiles, tested under 50 and 100 kPa are about 18.7 and 34.8 mm, respectively. While the permanent deformation occurred in identical samples with geotextiles are 13.5 and 22.1 mm, respectively. However, it is seen that the permanent deformation which occured when the deviatoric stress was 200 kPa in samples with and without geotextile reached the 35 mm deformation within 100 cycles. These results indicate that the effect of geotextiles on the performance of SFA systems is not significant at high stress levels due to the high levels of permanent deformation. This is attributed to the low strength of sabkha and high pore pressure generated at high pulses. Such phenomenon needs to be studied in some more details.

The permanent deformation at 100, 500, 1000 and 10000 load repetitions, for soaked samples with and without geotextiles tested under three deviatoric stress levels, were selected. These values were used in calculating the Indicator Ratio (I.R.) and the results are reported in Table 4.11.

The permanent deformation versus the stress level, for samples with and without geotextile is plotted in Figure 4.24 and 4.25. These figures indicate that the permanent deformation is increasing as the stress level increases. Furthermore, the inclusion of geotextile clearly decreases the deformation.

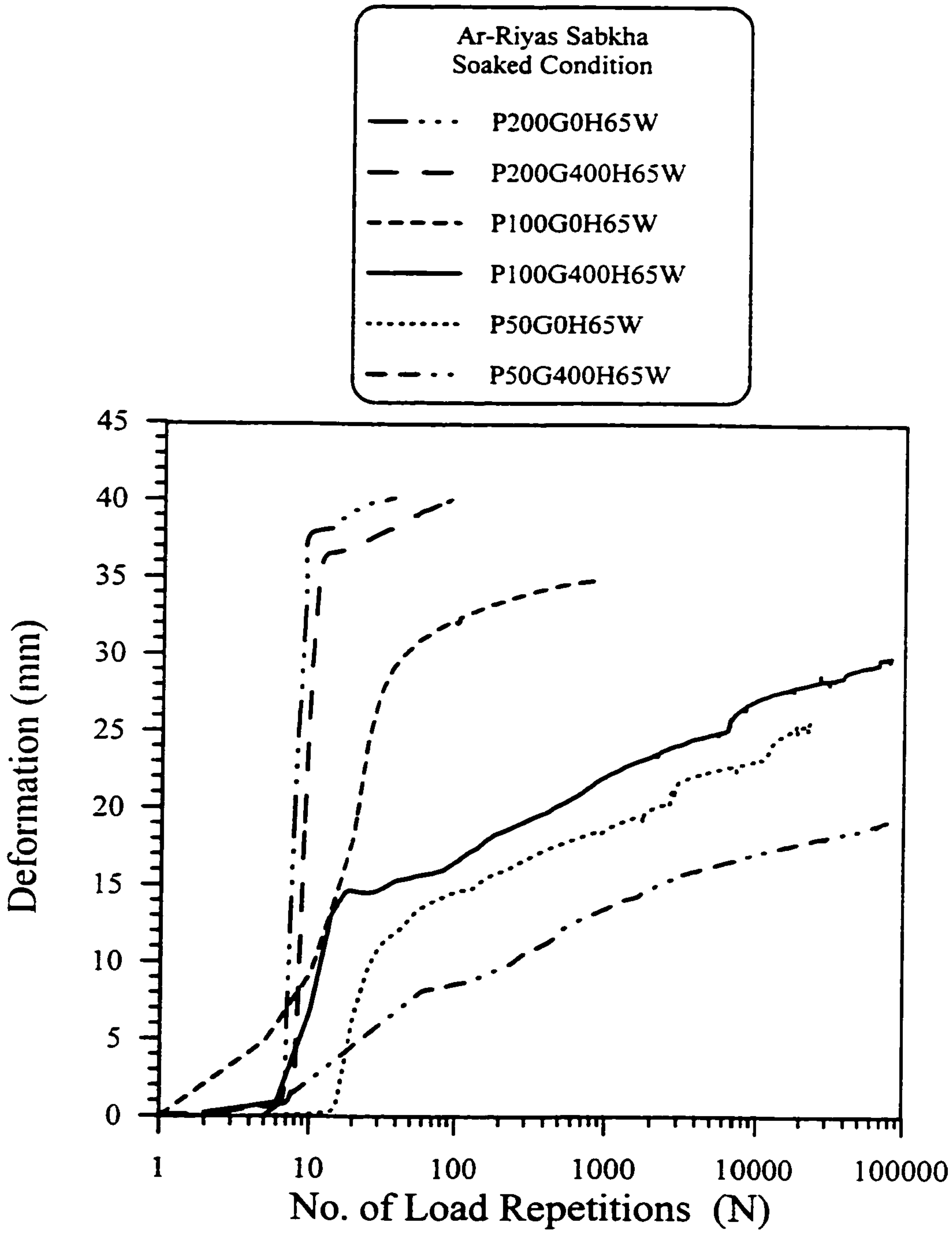


Figure 4.23: Effect of deviatoric stress on the performance of sabkha soil (with and without geotextile) under soaked condition

Table 4.10: Summary of the dynamic testing results considering the effect of deviatoric stress levels

Sample Code \ No. of Load Repetitions	Deformation (mm) 50	100	200	500	1000	10000
P50G0H65W (Soaked without Gtx.)	13.0	14.5	15.9	17.7	18.7	23.1
P50G400H65W (Soaked with Gtx.)	8.1	8.7	9.9	12.3	13.5	17.1
P100G0H65W (Soaked without Gtx.)	30.5	32.0	33.4	34.5	35.0	>35
P100G400H65W (Soaked with Gtx.)	15.5	16.5	18.4	20.2	22.1	27.1
P200G0H65W (Soaked without Gtx.)	>35	>35	>35	>35	>35	>35
P200G400H65W (Soaked with Gtx.)	>35	>35	>35	>35	>35	>35

Table 4.11: Summary of the dynamic testing results considering the effect of deviatoric stress level for selected No. of laod repetitions

	Gtx. Grade / Deviatoric Stress (kPa)	No. of Load Repetitions 100 G_0	100 A-400	100 IR	500 G_0	500 A-400	500 IR	1000 G_0	1000 A-400	1000 IR	10000 G_0	10000 A-400	10000 IR
Deformation (mm)	P_1=50	14.5	8.7	1.7	17.7	12.3	1.4	18.7	13.5	1.4	23.1	17.1	1.3
	P_2=100	32.0	16.5	1.9	34.5	20.2	1.7	34.8	22.1	1.6	38.0	27.1	1.4
	P_3=200	41.0	40.0	1.0	43.0	42.0	1.0	43.5	42.5	1.0	44.0	45.0	1.0

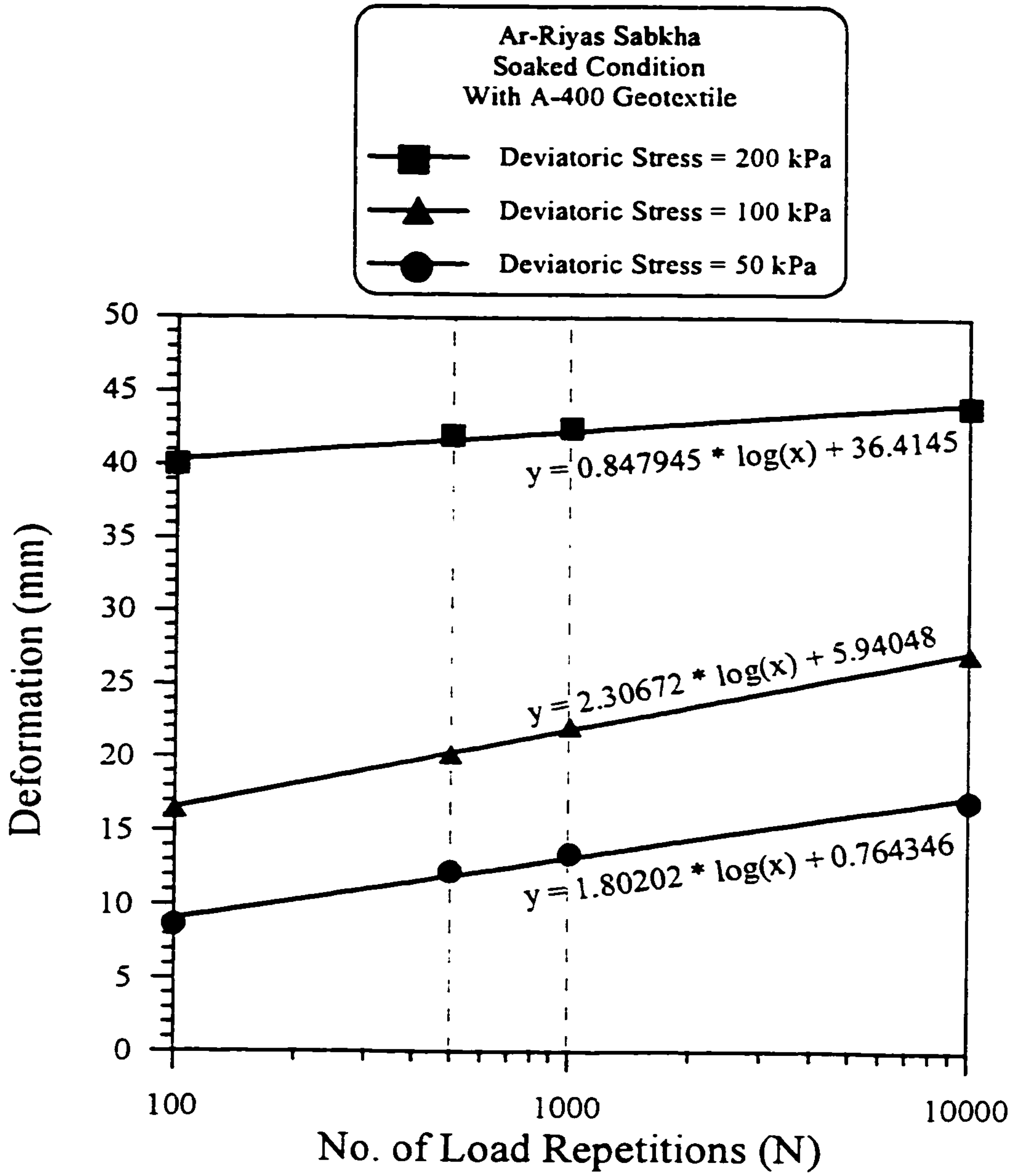


Figure 4.24: Effect of deviatoric stress level on the deformation for selected No. of load repetitions for sabkha with A-400 geotextile

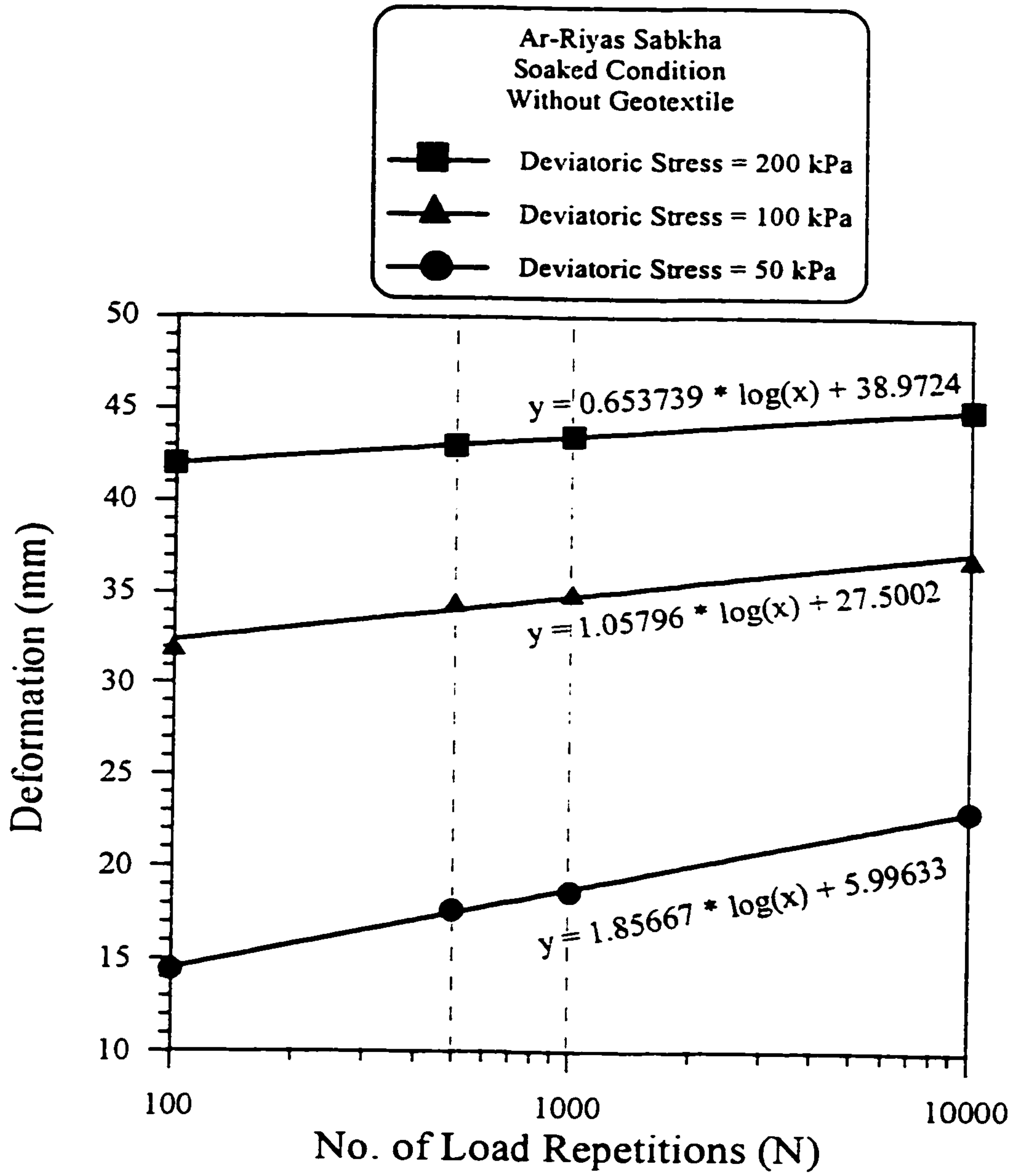


Figure 4.25: Effect of deviatoric stress level on the deformation for selected No. of load repetitions for sabkha without geotextile

The indicator ratio (I.R.) versus the stress level is presented in Figure 4.26. The data show that I.R. increases as the stress level increases from 50 to 100 kPa. However, the I.R. values decreased with the increase of stress level from 100 to 200 kPa. The I.R. value of the samples tested under 100 kPa is much higher than the indicator ratio of the sample, which were tested under 50 kPa and 200 kPa stress levels. This shows that the reduction in the permanent deformation due to the geotextiles is much higher in case of 100 kPa. For example, the reduction in the permanent deformation due to the inclusion of geotextiles at 500 load repetitions is about 41% in a sample tested under 100 kPa stress. While in an identical sample tested under 50 kPa, permanent deformation was reduced only 31% due to the inclusion of geotextile at the same no of load repetitions.

4.3.2.4 Effect of Geotextile Grades

The effect of geotextile grade on the performance of SFA systems is another variable investigated in this study. Two grades of non-woven Polypropylene geotextiles A-140, and A-400 were used. These two grades are differing in their physical characteristics including weight, thickness, tensile strength, permeability coefficient, etc. These properties were listed in Table 4.3.

The effect of the grade of geotextile on the permanent deformation of SFA systems was investigated under both as-molded and soaked conditions. Identical samples with 65 mm base (SSA layer) thickness were subjected to 100 kPa deviatoric stresses. The permanent deformation versus the number of load repetitions (N) of the soaked and as-molded samples are shown in Figures 4.27 and 4.28, respectively. The values of deformation at selected number of load repetitions are presented in Table 4.12.

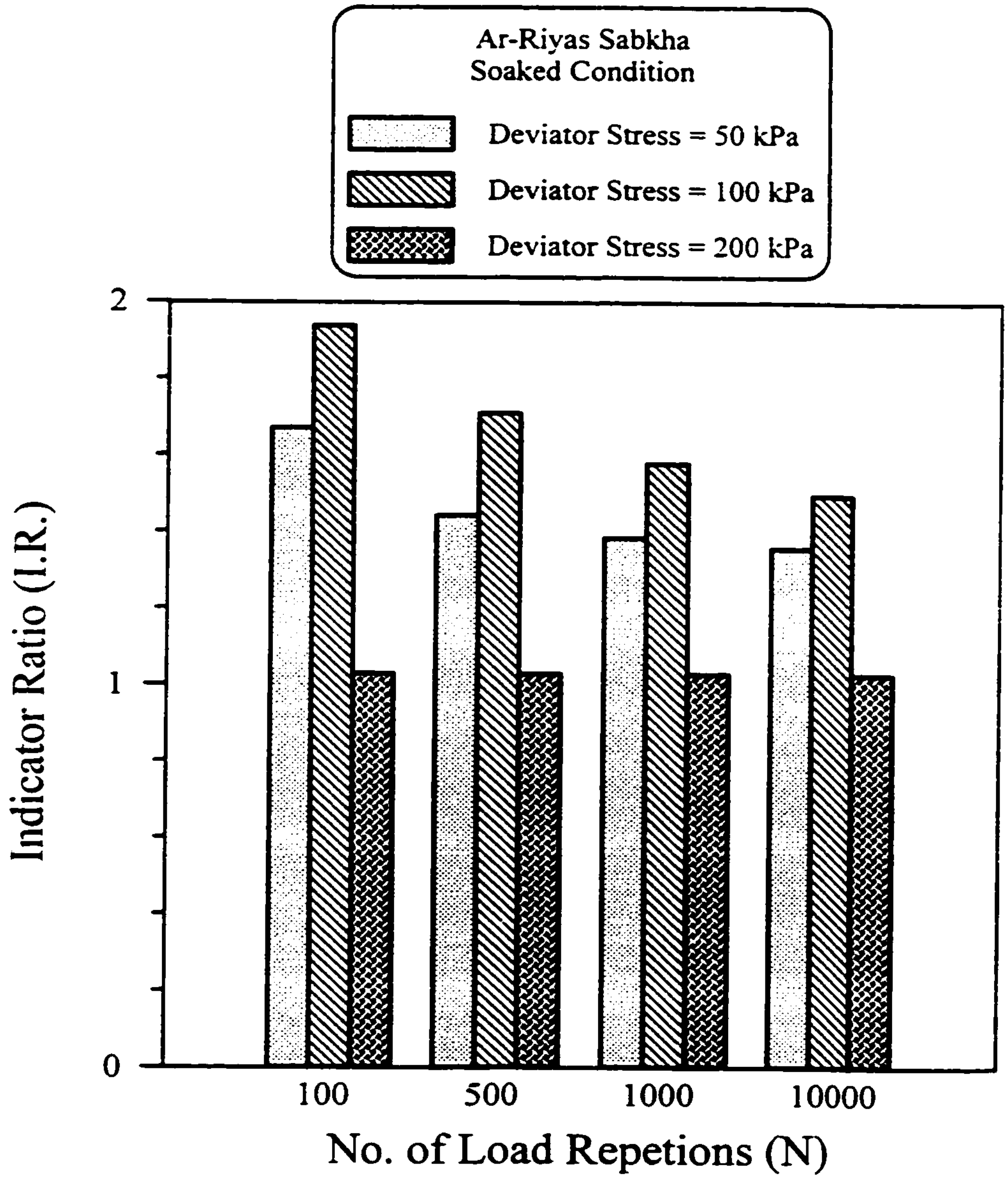


Figure 4.26: Indicator ratio versus selected No. of load repetitions for the effect of deviatoric stress on the performance of sabkha soil

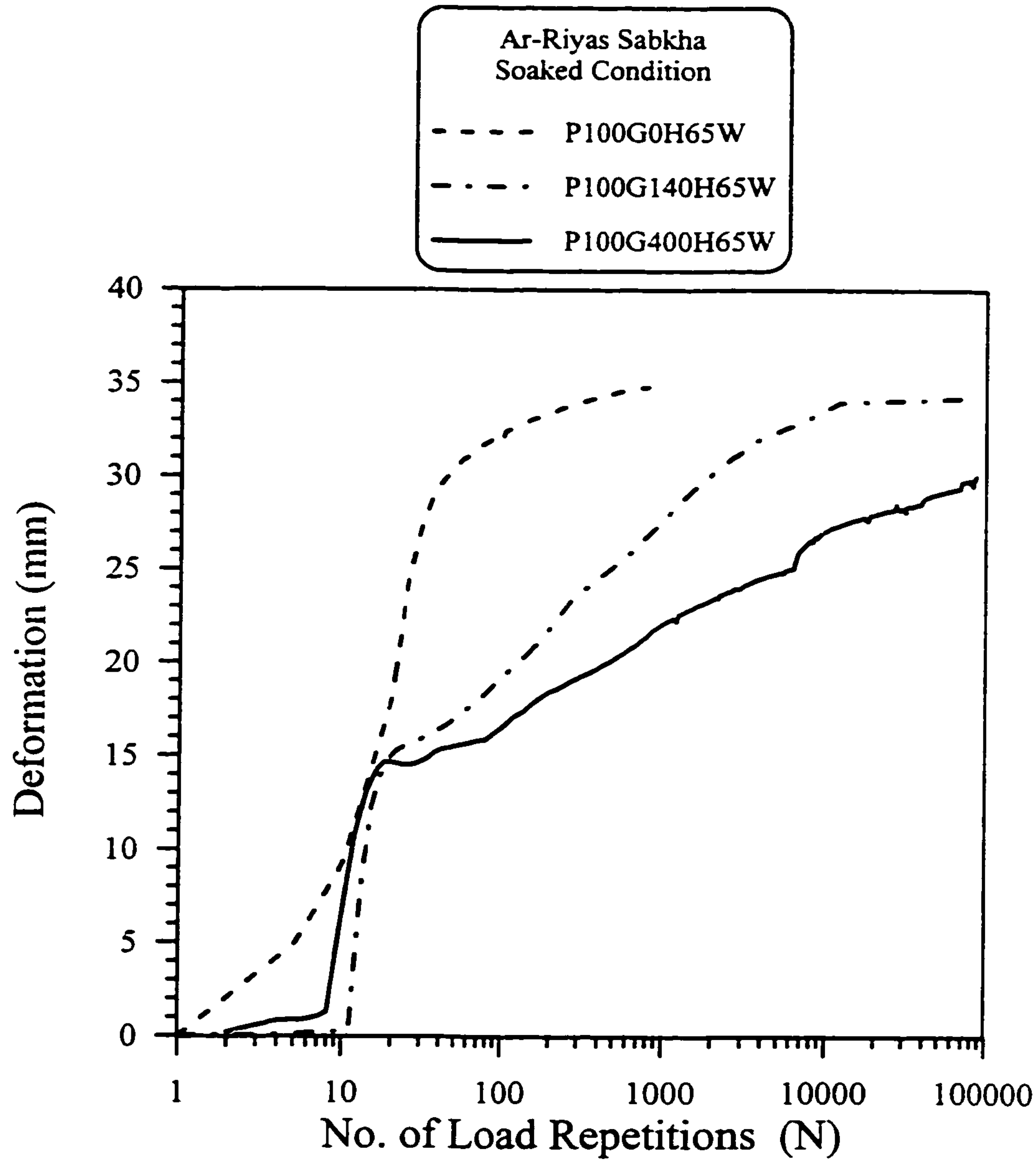


Figure 4.27: Effect of geotextile grade on the performance of sabkha soil under soaked condition

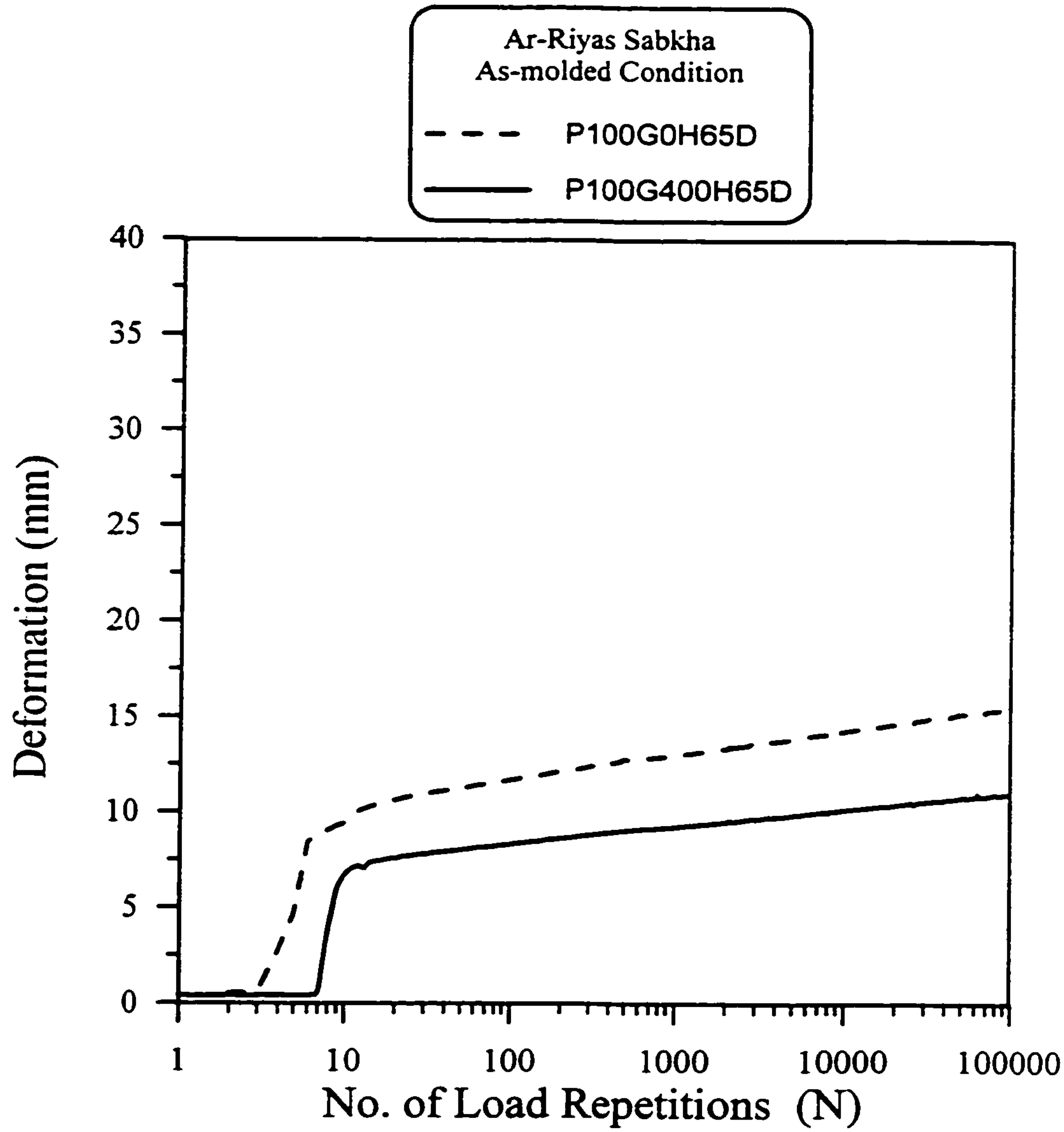


Figure 4.28: Effect of geotextile on the performance of sabkha soil (with and without geotextile) for as-molded condition

Table 4.12: Summary of the dynamic testing results considering the effect of geotextile grade

	Deformation (mm)					
No. of Load Repetitions / Sample Code	50	100	200	500	1000	10000
P100G0H65W (Soaked without Gtx.)	30.5	32.0	33.4	34.5	35.0	>35
P100G140H65W (Soaked with Gtx.)	17.0	19.2	21.9	25.2	27.7	33.5
P100G400H65W (Soaked with Gtx.)	15.5	16.5	18.4	20.2	22.1	27.1
P100G0H65D (As-molded without Gtx	11.3	11.7	12.1	12.7	13.0	14.3
P100G400H65D (As-molded with Gtx.)	8.0	8.3	8.6	9.0	9.2	10.1

The results in Figure 4.27 indicate that the geotextiles significantly increases the load-carrying capacity of the sabkha subgrades, which leads to a decrease in the permanent deformation of the SFA systems. The performance of the sample containing A-400 geotextile is better than that containing A-140. The permanent deformation for the two samples is 22.1 mm and 27.7 mm, respectively, at 1000 load repetitions. Similar behavior can be observed for the as-molded samples in Figure 4.28. The use of A-400 geotextile has reduced the deformation. However, the amount of deformation reduction is much less than that observed in the soaked samples. The permanent deformation for soaked samples with and without geotextiles are summarized for 100, 500, 1000 and 10000 load repetitions and reported in Table 4.13. From these values, the indicator ratio (I.R.) was calculated and reported in the same table. The permanent deformations of the different samples are shown in Figure 4.29. It is clearly seen that the permanent deformation at different load repetitions is the lowest in the sample with A-400. The indicator ratio (I.R.) calculated for the different grades of geotextiles is shown in Figure 4.30. It is clear from the Figure that highest indicator ratio (I.R.) is associated with A-400.

In order to compare the effect of geotextile on the improvement of load-carrying capacity of sabkha soil samples. A graph was plotted for the tensile strength of geotextiles versus the load required for 20, 25 and 30 mm of deformation as shown in the Figure 4.31. The data shows a simple linear relation between the load-carrying capacity of sabkha-geotextile system and tensile strength of geotextile for all three deformations. This clearly indicates that as the tensile strength of the geotextile increases, the load-

Table 4.13: Summary of the dynamic testing results considering the effect of geotextile grade on permanent deformation

	Geotextile Grade \ No. of Load Repetitions	100	500	1000	10000
Deformation (mm)	Without Geotextile	32.0	34.5	35.0	38.0
	A-140	19.2	25.2	27.7	33.5
	A-400	16.5	20.2	22.1	27.1
IR Value	A-140	1.7	1.4	1.3	1.1
	A-400	1.9	1.7	1.6	1.4

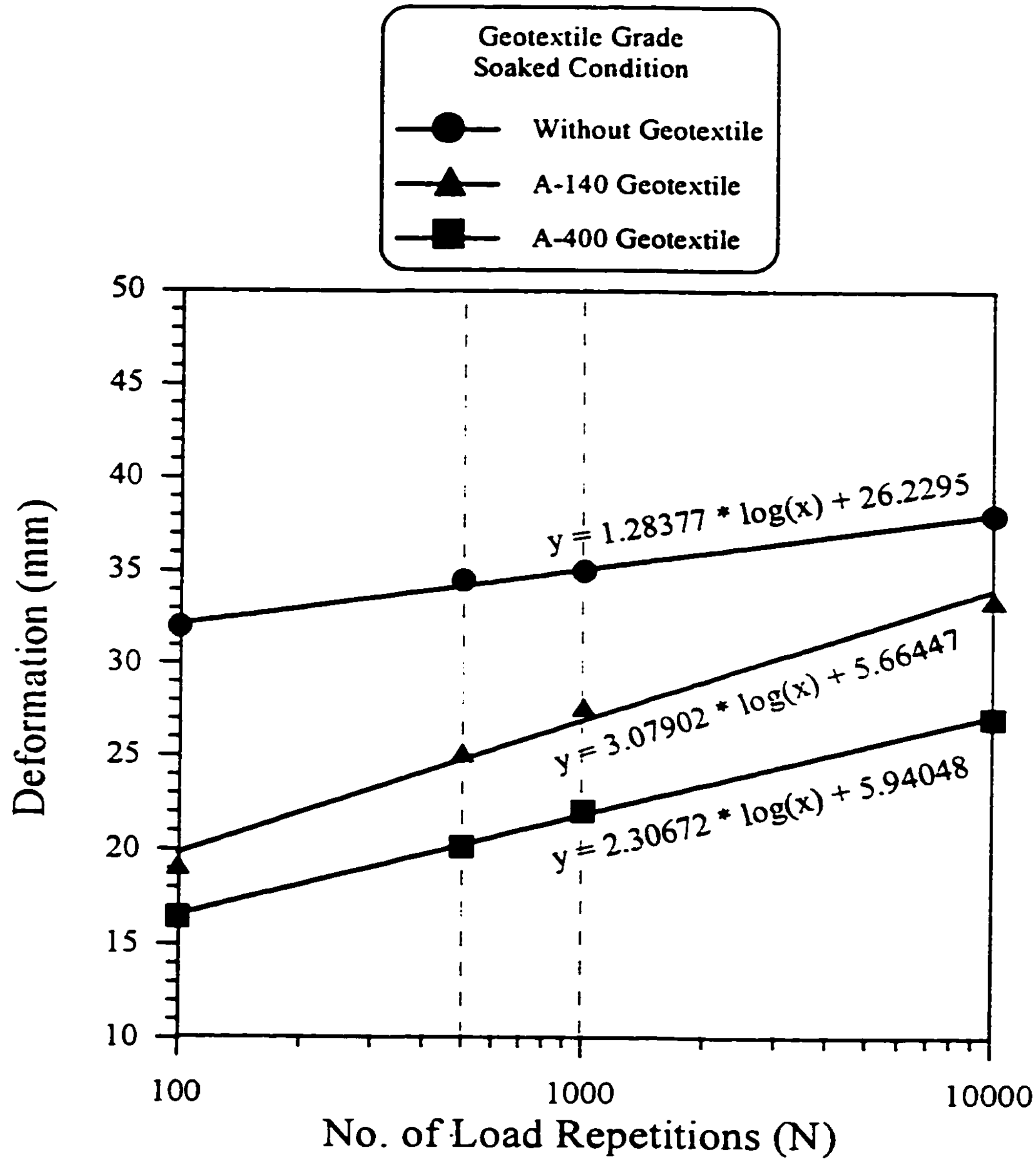


Figure 4.29: Effect of geotextile grade on the deformation for selected No. of load repetitions

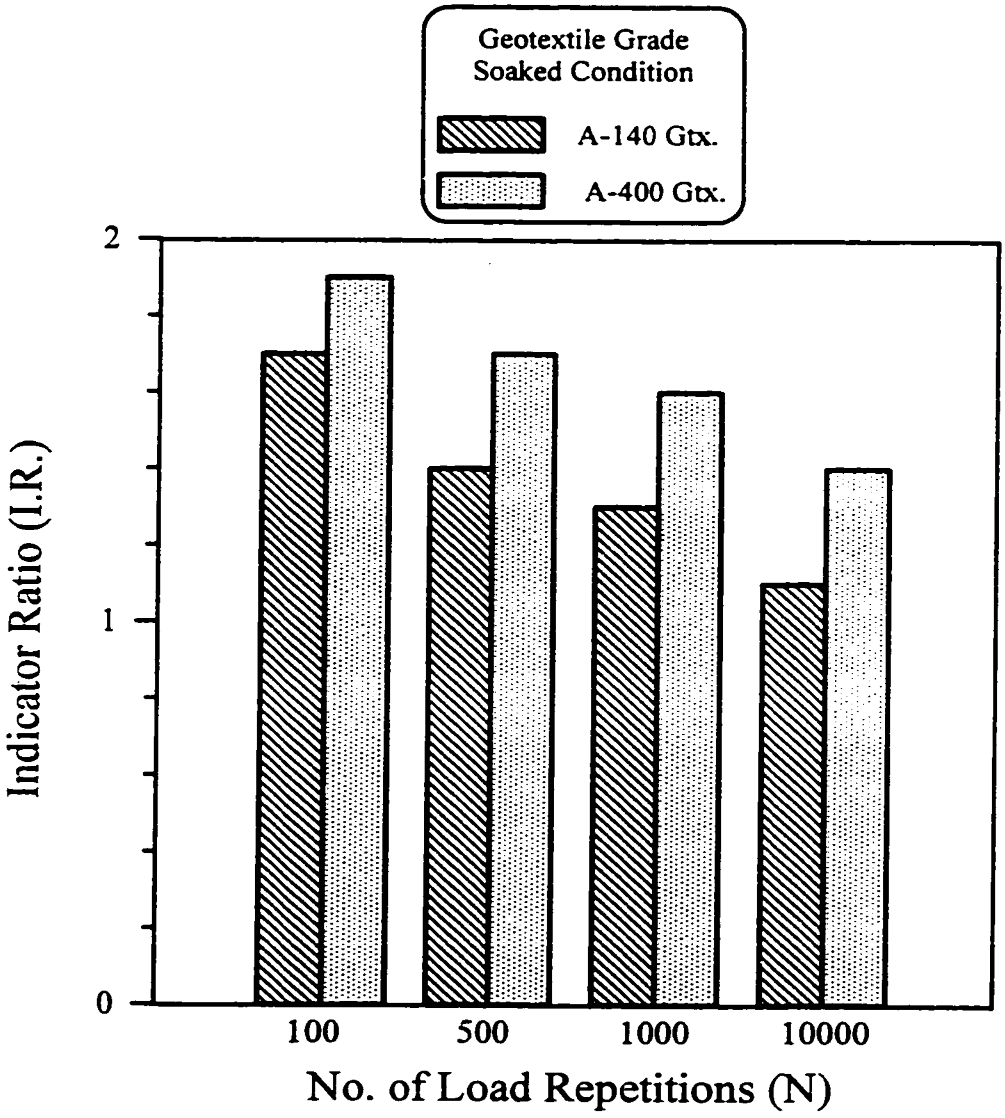


Figure 4.30: Indicator ratio versus selected No. of load repetitions for the effect of geotextile grade on the performance of sabkha soil

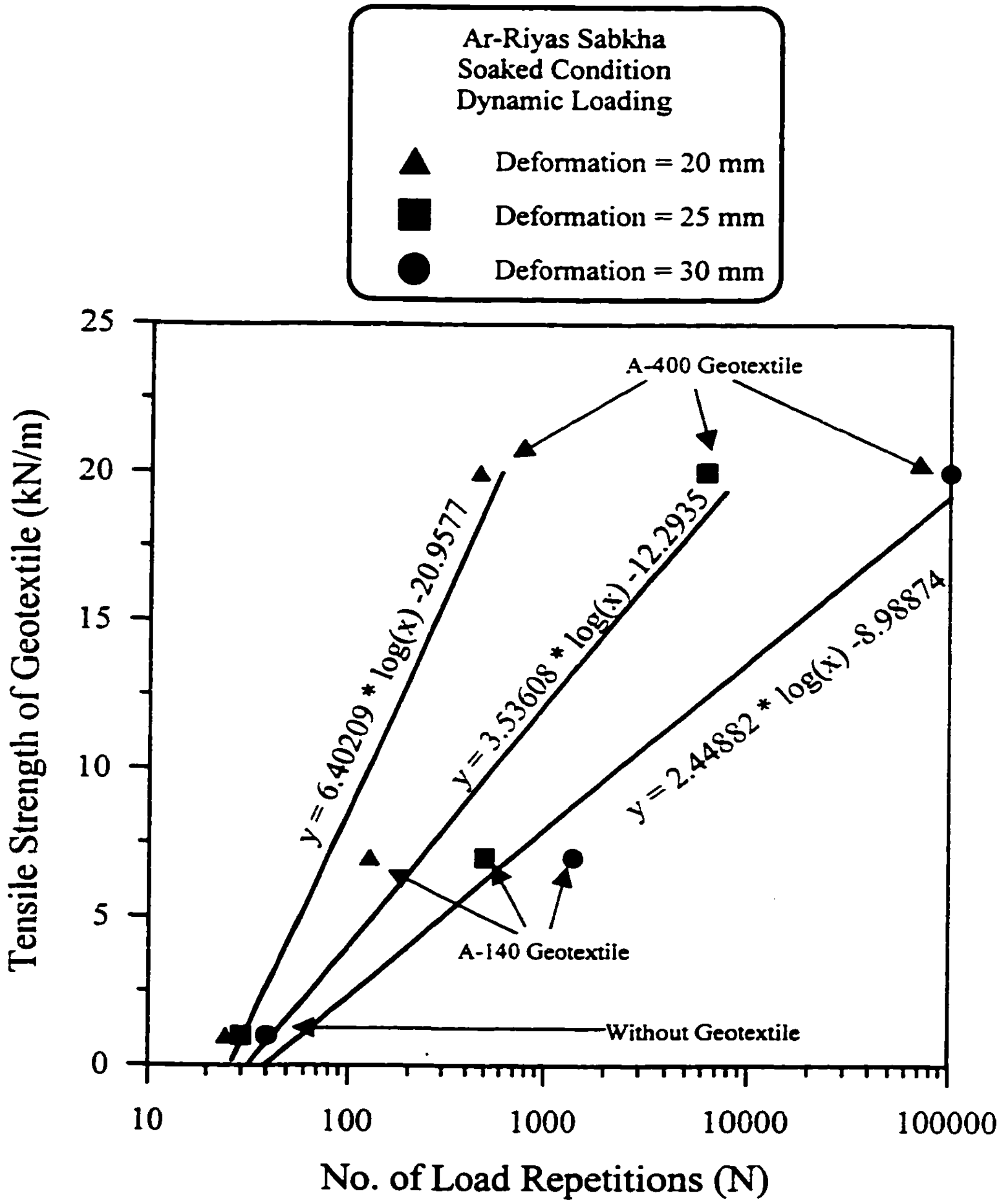


Figure 4.31: The effect of the tensile strength of geotextile on the load carrying capacity of sabkha soil for dynamic loading

carrying capacity of the system increases. Further testing is required to examine such behavior over a wide range of values.

Based on the findings, it is clearly seen that the grade of geotextile is significantly affecting the performance of sabkha-geotextile system whereby the permanent deformation decreases as the tensile strength of the geotextile increases, especially for the soaked samples. The geotextile with highest tensile strength (A-400) showed the highest reduction in the permanent deformation as compared to the geotextile with lower tensile strength (A-140).

4.4 Statistical Analysis

4.4.1 Analysis Of Variance (ANOVA)

Statistical analysis was performed for the collected data to study the significance of the variables and to check statistically that the effect of each variable is significantly different from each other. The Analysis of Variance (ANOVA) for the single factor model was used for this analysis. In general, the purpose of the analysis of variance is to test for the significance difference between the means of variables or treatments (μ). The appropriate procedure for testing the equality of a treatment means is to check the following hypothesis (Montgomery, 1991).

$$H_0: \mu_1 = \mu_2 = \ldots\ldots\ldots\ldots = \mu_a$$
$$H_1: \mu_i \neq \mu_j$$

Where μ_i is the overall variable means for the different parameters such as geotextile grade, base thickness, loading type (static and dynamic) and moisture condition (as-molded and soaked). If H_0 is true, it means that there is no difference in treatment means and if H_0 is not true then it means that there is significant difference between the treatments means and it is unlikely that treatment means are equal.

The analysis of variance (ANOVA) calculations were performed using the statistical tools of Microsoft Excel software. Statistically significant results are obtained whenever p-level is less than the selected significance level (S.L). This means that for 95% S.L, p-level should be less than 0.05 in order to achieve significant effect of any factor. More technically, the value of the p-level (the term first used by Brownlee, 1960) represents a decreasing index of the reliability of the result. The higher the p-level the less are the chances that the observed relation between the respective variables in the sample is a reliable indicator of the relation between the respective variables in the population. Specifically, the p-level represents the probability of error that is involved in accepting the observed results as valid, that is, as "representative of the population". For example, a p-level of .05 (i.e., 1/20) indicates that there is a 5% probability that the relation between the variables found in the selected sample is insignificant. In most of the analysis, the p-level of .05 is customarily treated as a "border-line for an acceptable" error level.

In addition, an alternative measure of significance is the use of the F-statistic, which gives the ratio of variability due to regression to the variability that is not explained. It is desirable that this value is as high as possible such that the probability of its improvement is very low.

Summary of ANOVA analysis for the effect of the different geotextiles grades is presented in Table 4.14. The mean square value (320.03) between treatments is much greater than the within-treatment or error mean square (18.33). This indicates that it is unlikely that the treatment means are equal. More formally, the F ratio can be computed (i.e. $F_0 = 320.03/18.33 = 17.45$) and compared this to $F_{crit} = 6.36$. Since $F_0 > F_{crit}$, H_0 is rejected and it can be concluded that the treatment means are different, that is, the grade of geotextile significantly affects the deformation. This can be confirmed by the low p-level ($0.0001<0.05$), showing the strong significance of geotextile grades.

Table 4.15 presents the ANOVA summary for the effect of dynamic loading for samples with and without geotextile. In the samples without geotextile, F_0=128 which is higher than the $F_{crit} = 6$, and the p-level (3.7E-10) value is also very small ($p <$ alpha). These values show that the treatment means differ, that is, the dynamic loading effect is

TABLE 4.14: ANOVA summary of the effect of geotextile grades

Groups	Count	Sum	Average	Variance
P100G0H65W	6	203.19	33.8650	6.6449
P100G140H65W	6	144.39	24.0650	36.1544
P100G400H65W	6	117.51	19.5850	12.2052

ANOVA

Source of Variation	SS	df	MS	F_0	P-value	F crit
Between Groups	640.0576	2	320.0288	17.4547	0.00012143	6.359
Within Groups	275.02225	15	18.33482			
Total	915.07985	17				

TABLE 4.15: ANOVA summary of the effect of dynamic loading

a) Without geotextile

Groups	Count	Sum	Average	Variance
P50G0H65W	6	102.79	17.13167	12.7302967
P100G0H65W	6	201.19	33.53167	4.00353667
P200G0H65W	6	243	40.5	3.5

ANOVA

Source of Variation	SS	df	MS	Fo	P-value	F crit
Between Groups	1727.193344	2	863.5967	128.0425	3.7359E-10	6.359
Within Groups	101.1691667	15	6.744611			
Total	1828.362511	17				

b) With geotextile

Groups	Count	Sum	Average	Variance
P50G400H65W	6	69.57	11.595	11.41187
P100G400H65W	6	117.51	19.585	12.20515
P200G400H65W	6	231	38.5	3.5

ANOVA

Source of Variation	SS	df	MS	Fo	P-value	F crit
Between Groups	2290.9927	2	1145.496	126.7281	4.0191E-10	6.359
Within Groups	135.5851	15	9.039007			
Total	2426.5778	17				

statistically significant. Similar pattern can be seen in the samples with geotextile, where $F_0 > F_{crit}$ ($F_0 = 126$ and $F_{crit} = 6$) and p-level = 4.0E-10, showing that the effect of dynamic loading is still significant and the inclusion of geotextile has brought some improvement as compared to the samples without geotextiles.

ANOVA summary for the effect of base thickness is shown in Table 4.16. In the samples without geotextile, $F_0=33$ which is higher than $F_{crit} = 6$, and the p-level (2.7E-6) value is also small (p < alpha). These values show that the treatment means differ, that is, the base thickness effect is statistically significant. In the samples with geotextile, $F_0 = 8$ and $F_{crit} = 6$ and p-level = 0.003 (p < alpha), showing that the inclusion of geotextile has reduced the effect of base thickness but the variable base thickness is important and it has significance effect on the load-carrying capacity.

ANOVA summary for the effect of soaking is presented in Table 4.17. In the samples without geotextile, $F_0=122$ which is much higher than the $F_{crit} = 10$, and the p-level (6.1E-7) value is also very small (p < alpha). These values show that the treatment means differ, that is, the effect of soaking is statistically significant. Similar pattern can be seen in the samples with geotextile, where $F_0 > F_{crit}$ ($F_0 = 53$ and $F_{crit} = 10$) and p-level = 2.5E-5, showing that the effect of soaking is still significant and the inclusion of geotextile has brought improvement in the load carrying capacity as compared to the samples without geotextiles. These results show that in both cases, with and without geotextiles, the effect of soaking is significant.

Analysis of variance was also performed for all the variables together. Table 4.18 shows the ANOVA summary for this analysis. This table shows that the $F_0 > F_{crit}$ ($F_0 = 53$ and $F_{crit} = 1$) and p-level = 6.0E-29, indicating that all treatment means differ

TABLE 4.16: ANOVA summary of the effect of base thickness

a) Without geotextile

Groups	Count	Sum	Average	Variance
P100G0H33W	6	225.57	37.595	14.72671
P100G0H65W	6	201.19	33.53167	4.00353667
P100G0H98W	6	119.73	19.955	26.65843

ANOVA

Source of Variation	SS	df	MS	Fo	P-value	F crit
Between Groups	1024.012311	2	512.0062	33.84145	2.7547E-06	6.359
Within Groups	226.9433833	15	15.12956			
Total	1250.955694	17				

b) With geotextile

Groups	Count	Sum	Average	Variance
P100G400H33W	6	148.78	24.79667	19.1664667
P100G400H65W	6	117.51	19.585	12.20515
P100G400H98W	6	95.71	15.95167	9.34297667

ANOVA

Source of Variation	SS	df	MS	Fo	P-value	F crit
Between Groups	237.1932111	2	118.5966	8.738631	0.00304676	6.359
Within Groups	203.5729667	15	13.57153			
Total	440.7661778	17				

TABLE 4.17: ANOVA summary of the effect of soaking

a) Without geotextile

Groups	Count	Sum	Average	Variance
P100G0H65W	6	201.4	33.56667	4.12782667
P100G0H65D	6	65.03	10.83833	21.1508567

ANOVA

Source of Variation	SS	df	MS	Fo	P-value	F crit
Between Groups	1549.731408	1	1549.731	122.6117	6.1988E-07	10.044
Within Groups	126.3934167	10	12.63934			
Total	1676.124825	11				

b) With geotextile

Groups	Count	Sum	Average	Variance
P100G400H65W	6	117.49	19.58167	12.2297367
P100G400H65D	6	53.29	8.881667	0.57857667

ANOVA

Source of Variation	SS	df	MS	Fo	P-value	F crit
Between Groups	343.47	1	343.47	53.63235	2.531E-05	10.044
Within Groups	64.04156667	10	6.404157			
Total	407.5115667	11				

TABLE 4.18: ANOVA summary for all varibles

Groups	Count	Sum	Average	Variance
P100G0H65W	6	203.19	33.865	6.64487
P100G140H65W	6	144.39	24.065	36.15443
P100G400H65W	6	117.51	19.585	12.20515
P50G0H65W	6	102.79	17.13167	12.7302967
P200G0H65W	6	243	40.5	3.5
P50G400H65W	6	69.57	11.595	11.41187
P200G400H65W	6	231	38.5	3.5
P100G0H33W	6	225.57	37.595	14.72671
P100G0H98W	6	119.73	19.955	26.65843
P100G400H33W	6	148.78	24.79667	19.1664667
P100G400H98W	6	95.71	15.95167	9.34297667
P100G0H65D	6	65.03	10.83833	21.1508567
P100G400H65D	6	53.29	8.881667	0.57857667

ANOVA

Source of Variation	SS	df	MS	Fo	P-value	F crit
Between Groups	8777.319618	12	731.4433	53.48894	6.0753E-29	1.90
Within Groups	888.8531667	65	13.67466			
Total	9666.172785	77				

significantly. The results of the analysis show that all variables including moisture condition, geotextile grade, base thicknesses, and loading type play a fairly significant role towards the variation in the load-carrying capacity values. This stronger correlation can be confirmed by observing their respective p-levels as shown in the tables.

4.4.2 ELSYM5 Analysis Results

ELSYM5 is a computerized procedure that models a three-dimensional idealized elastic layered pavement system. The pavement may be loaded with one or more identical uniform circular loads normal to the surface of the pavement. The program computes the various components of stresses, strains, and displacements along with principal values at locations specified by the user, within the layered pavement. The ELSYM5 computer program was developed at the University of California at Berkeley. It is a modification of the LAYER5 program allowing consideration of multiple loads as well as the presence of rigid base below the subgrade.

In this investigation, the program was used in order to calculate the increase in the computed resilient modulus (M_R) value, due to the use of geotextiles, in sabkha-geotextile system. For this purpose two layered model was used in which deformation was fixed at 30 mm (1.18 inch) and the load required for this deformation was obtained from the static loading results. Several trials were performed in order to come up with the M_R value of sabkha without geotextile. In these trials, load required for 30 mm deformation and M_R value for steel slag aggregate (SSA) were kept constant and M_R value of sabkha was varied until 30 mm deformation was achieved. This M_R value was considered an original value for sabkha soil.

Whenever geotextiles were used the load required for 30 mm deformation was taken from the experimental results of the sabkha samples in which the geotextile was used. In a similar way to that discussed above, load and M_R value of SSA were kept constant and the M_R value of sabkha was varied to achieve the 30 mm deformation. This new M_R value of sabkha is the result of improvement brought about by the inclusion of geotextile in the sample. In a similar manner, trials were performed for geotextiles A-300 and A-400. Results of these runs are presented in Table 4.19 and Figure 4.32. These results indicate that the inclusion of A-140 geotextile has increased the M_R value sabkha soil layer from 30 psi (without geotextile) to 40 psi (with A-140), which is an increase of about 33% in the M_R value of sabkha layer. Similarly when the A-300 and A-400 geotextiles were added to the system, the M_R value of sabkha layer were increased to 60psi (with A-300) and 80 psi (with A-400) as compared to the M_R value of 30 psi (without geotextile). This shows an increase of 100 and 166 percent in the M_R value of sabkha layer due the inclusion of geotextiles A-300 and A-400, respectively.

Table 4.19: Summary of the results of ELSYM5 analysis

Geotextile	Load (kN) (Experimental)	M_R (psi)		% increase in M_R Value
		Slag	Sabkha	
No Gtx.	2.0	150	30	-
A - 140	2.8	150	40	33
A - 300	6.0	150	60	100
A - 400	6.5	150	80	166

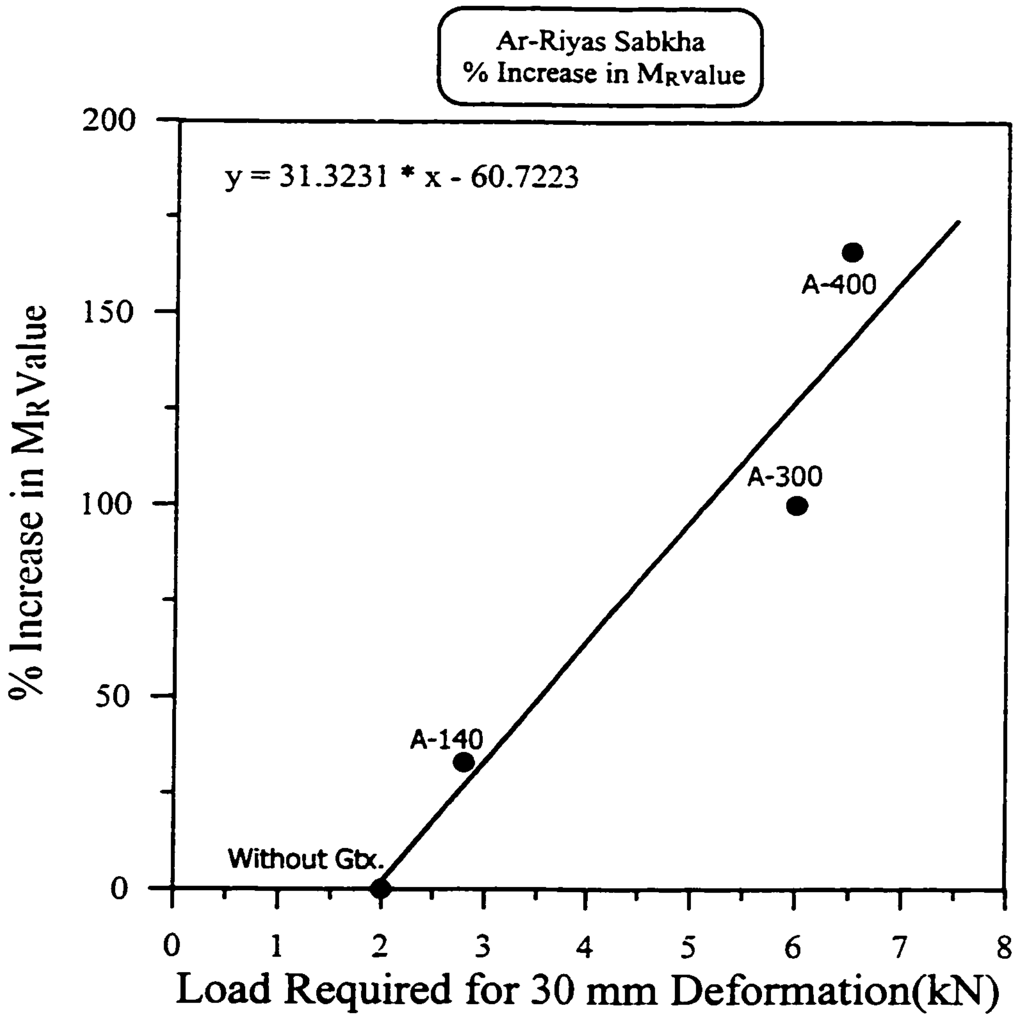


Figure 4.32: Results of Elsym 5 software analysis showing the percent increase in M_R value due to the inclusion of geotextiles

Chapter 5

SUMMARY CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the findings of the results obtained throughout the research program. Recommendations have been stated for the extension of this research program.

5.1 Summary

This investigation was conducted to assess the effect of geotextile on the performance of sabkha soil. Several parameters were investigated including the effect of soaking, geotextile grade, subbase thickness, loading condition and the lateral extent of geotextile. In addition, the effect of cement addition on the improvement of sabkha was studied and compared with the performance of SFA systems. Based on the results developed in this investigation, the conclusions are presented in the next section.

5.2 Conclusions

- The soaked sabkha samples showed much lower load-carrying capacity compared to the as-molded samples.

- The sabkha samples with the geotextiles displayed significant improvement in the load-carrying capacity of sabkha soil under soaked conditions. However, the degree of improvement with the use of geotextile, in the as-molded sabkha samples was found to be much less than the improvement in the soaked samples.
- The Effectiveness of the geotextiles in reducing the permanent deformation diminishes with the increase in the thickness of the SSA base layer.
- The effect of geotextile in improving the load-carrying capacity of sabkha soil becomes negligible at higher deviatoric stress (i.e. 200 kPa) level.
- The soil samples with geotextile of higher tensile strength and greater thickness showed high load-carrying capacity and thus less deformation compared to those with lower tensile strength geotextiles.
- The improvement in the load-carrying capacity of sabkha samples with five percent Portland cement was lower (79%) than the improvement obtained using A-400 geotextiles.
- The improvement in the load-carrying capacity in sabkha samples with higher percentages (7% and 10%) of Portland cement was little higher, 107% and 119% respectively, than the improvement brought about by the use of A-400 geotextile.
- The geotextile must have some minimum extent beyond the loading plate to be of any benefit and larger the geotextile area the more the improvement in the load-carrying capacity.
- The inclusion of geotextile can save in the aggregate base thickness as compared to the systems without geotextile.

- Geotextile can be used effectively to overcome the problems associated with the low strength of sabkha, when it is used as a subgrade, in road construction.

5.3 Recommendations

Based on this study the following recommendations can be made for any future study:

- A large-scale field study with different test sections is strongly recommended to evaluate the effect of geotextiles on the performance of sabkha subgrades. The system should be loaded to failure (maximum deformation) to understand the complete phenomenon of geotextile performance in soil fabric aggregate systems.
- A study should also be carried out to estimate the effect of the paved layer, in the laboratory or in the field, on the sabkha soil.
- Different brands and grades of geotextile should be used to evaluate their effects on the sabkha-geotextile-aggregate systems.

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